N84-28682

5030-569
Electric and Hybrid Vehicle
System Research and Development Project

DOE/CS-54209-14
Distribution Category UC-96

Hybrid Vehicle Assessment
Phase I
Petroleum Savings Analysis

R. Levin, Task Manager
S. Liddle
G. Deshpande
M. Trummel
H. Vivian

March 1984

Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL Publication 84-15

5030-569
Electric and Hybrid Vehicle
System Research and Development Project

DOE/CS-54209-14
Distribution Category UC-96

Hybrid Vehicle Assessment Phase I Petroleum Savings Analysis

R. Levin, Task Manager
S. Liddle
G. Deshpande
M. Trummel
H. Vivian

March 1984

Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL Publication 84-15

Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

ABSTRACT

This report presents the results of a comprehensive analysis of near-term electric-hybrid vehicles. Its purpose was to estimate their potential to save significant amounts of petroleum on a national scale in the 1990s. Performance requirements and expected annual usage patterns of these vehicles were first modeled. The projected U.S. fleet composition was estimated, and conceptual hybrid vehicle designs were conceived and analyzed for petroleum use when driven in the expected annual patterns. These petroleum consumption estimates were then compared to similar estimates for projected 1990 conventional vehicles having the same performance and driven in the same patterns. Results are presented in the form of three utility functions and comparisons of several conceptual designs are made. The Hybrid Vehicle (HV) design and assessment techniques are discussed and a general method is explained for selecting the optimum energy management strategy for any vehicle-mission-battery combination. A discussion of lessons learned during the construction and test of the General Electric Hybrid Test Vehicle is also presented. Conclusions and recommendations are presented, and development recommendations are identified.

ACKNOWLEDGMENT

Hybrid Vehicle Assessment Task Members

Task Manager	R. Levin
Vehicle Requirements	G. Deshpande
Power System Analysis	S. Liddle H. Vivian M. Trummel
HV Engineering	G. Klose H. Fortgang
Modeling and Simulation	T. Hsieh R. Slusser P. Chapman
Report Publication	M. Gyamfi C. Marsh

Task members gratefully acknowledge the contributions made by other members of the JPL Electric and Hybrid Vehicle Project. Contributions by T. Almaguer, R. Banes, E. Cynkin, D. Kurtz, J. Langendoen, J. Long, J. Park, T. Price, V. Roan, and J. Rowlette were most valuable. Typing and editing were performed by Cheryl Johnson, Racheal Porter, and Shirley Stroup. Their assistance is gratefully acknowledged.

The Electric Hybrid Vehicle R&D Project is conducted by JPL under Contract NAS7-918, Task Order RE-152, Amendment 170 and DOE/NASA Interagency Agreement DEAI01-78CS54209.

CONTENTS

Figures

Tables

Part One
Summary

SUMMARY

INTRODUCTION

The Jet Propulsion Laboratory (JPL) Electric and Hybrid Vehicle (EHV) System Research and Development (R&D) Project is an element of the U.S. Department of Energy (DOE) Office of Vehicle and Engine Research and Development. The goal of this DOE activity is to maximize the national petroleum savings potential of EHVs by developing those technologies required for widespread EHV use, by understanding the attributes of hybrid vehicles, and by identifying vehicles and missions that offer the potential for significant petroleum savings.

With some 40% of national petroleum consumption attributable to personal transportation, hybrid vehicles (HV) can offer great promise for the reduction of petroleum-based fuel consumption if they enter the national fleet in significant numbers. By using electrical energy, they become in effect coal-powered or nuclear-powered vehicles. The HV, however, is generally regarded by the automobile industry as a promising, but high-risk concept with insufficient near-term potential to stimulate significant private sector development initiatives. In order to determine the value of further engineering development of the HV concept, the Hybrid Vehicle Assessment (HVA) was begun. This report summarizes the results of the first phase of the HVA, the Petroleum Savings Analysis.

GENERAL

A hybrid vehicle has two (or more) energy storage and conversion subsystems, one of which is a secondary (rechargeable) battery-electric motor contoller. The preferred second subsystem, by virtue of its superior specific power and specific energy, is a conventional heat engine-petrochemical fuel system. The term "hybrid vehicle" used throughout this report is generic and implies a dual-traction subsystem vehicle.

Early development, testing, and limited introduction of HV designs into the national fleet offer an excellent way to market the concept of electric drive without incurring its most serious penalty, the so-called range limitation (long battery recharge times). Near-term traction batteries require much longer recharge times than the typical gasoline tank refill time, and this characteristic of electric systems is interpreted by the driving public as a range limitation. A hybrid vehicle, regardless of its configuration and with suitable energy management strategy, offers an alternative. When the HV traction battery is unable to deliver the required range or performance, the heat engine can supply the required power. Thus, although the HV requires a more complex vehicle and control system, it offers transitional advantages to pure electric vehicles.

There are two energy-related issues confronting the automobile user today, the availability of fuel and its price. Sufficient gasoline may be available at an unattractive price (price rationing), or scarcity of fuel at a government-controlled price may occur (supply rationing).

The HV is attractive in either of these scenarios. If gasoline is expensive or in short supply, the HV offers advantages because of its vastly superior fuel economy for trips within its electric range. (For trips beyond its electric range, fuel economy is inferior to that of a comparable conventional car because of the added weight of the unused electrical drive subsystem.) In the extreme case of complete unavailability of gasoline, pure electric operation could be driver-selected, provided that the necessary override logic is available within the HV energy management system and reduced acceleration performance is accepted, a small price to pay for mobility in such circumstances.

Because the HV system (vehicle plus centrally generated electric power and purchased petroleum fuel) is not generally an energy saver, and because it is expected to have a higher first cost than a comparable conventional car, it must offer other advantages, such as economy or mobility, if it is to become competitive. Advantages of mobility are ends in themselves. Mobility in a petroleum-scarce scenario has proven value to the consumer. Economy can be provided by Government (Federal and/or State) programs wherein national objectives (petroleum savings) are met by providing economic incentives to stimulate the desired action.

There are a number of possible incentives that could be offered to operators of hybrid vehicles if petroleum savings become a high priority objective. Direct subsidies to manufacturers and/or purchasers to offset the higher HV purchase price are one possibility. Low interest loans, partial tax write-offs, accelerated depreciation schedules for businesses, etc., are also possible. Replacement battery costs could also be incentives. Battery suppliers could lease traction batteries, provide extended maintenance agreements or offer repurchase agreements to owners to avoid the possibilities of expensive battery replacement costs. Operators of HVs could also be given off-peak energy rates by utilities for nighttime charging, although the availability of off-peak electric energy may become an important issue. A number of alternatives exist. They are mentioned here, not as recommendations, but as potential attributes of a national HV program in a petroleum-scarce environment.

As a result of the modeling and simulation activities within the HVA and on the basis of the currently limited test results on the General Electric Company Hybrid Test Vehicle (HTV), it has become clear that the concept of vehicle hybridization does not offer promise as an overall energy-saving concept. Hybridization is a petroleum saver when the burden of conversion to electrical energy is transferred to another fuel (coal, nuclear, etc.). However, the electrical generation, transmission, battery charge, and discharge process generally have no better than rough efficiency parity with the analogous petroleum energy conversion cycle (refining, distribution, combustion) within the conventional car. The use of non-petroleum-generated electric power (principally coal) seems to be more efficient than the liquefaction of coal to make gasoline for a spark-ignited automobile engine (Reference 1).

Futhermore, the specific energy of petroleum fuel is some 50 times greater than the specific energy of even the best traction battery. The specific power of conventional heat engines is some five times greater than the specific power of battery-motor subsystems. From either an energy point

of view or from a power point of view, the answer is the same. The petroleum-fueled heat engine is, in energy conservation, usually superior to an electric or a hybrid power plant. In an energy conservation scenario, hybridization, therefore, may be disadvantageous; in a petroleum-scarce scenario, however, it can offer substantial petroleum savings if properly implemented on a national scale.

This report describes the HVA conducted by the JPL Electric and Hybrid Vehicle Project during the period from October 1981 to September 1983. It was a near-term assessment with an assumed end point of 1990. The purposes of the study were to:

(1) Understand the attributes of HVs.

(2) Develop a general methodology for understanding HVs and their design parameters.

(3) Identify the most appropriate missions for HVs and develop realistic driving patterns for further use in computer modeling and simulation work. Estimate the performance characteristics required for safe operation, consumer acceptability, and acceptable traffic impact.

(4) Investigate alternative HV configurations (including propulsion subsystems, controls, and energy storage subsystems) and make assessments of HVs as petroleum savers and as operational vehicles. Include modeling and simulation of conceptual designs and compare actual HTV test data with model prediction and validation techniques for prediction of petroleum consumption, component efficiencies, and vehicle acceleration performance.

(5) Identify critical technologies required and develop operating strategies for the most promising HV configurations.

(6) Assess the potential of the most promising hybrid vehicle conceptual designs to reduce U.S. petroleum consumption.

(7) Summarize the lessons learned during construction and test of the General Electric HTV.

STUDY METHOD

The analysis began with the DOE program objective to achieve national petroleum savings and was based on the following assumptions:

(1) Future mobility (petrochemical) fuel shortages are likely, and substantial petroleum savings will be required.

(2) Performance characteristics of successful HVs must provide the projected performance characteristics of 1990 conventional vehicles. Safety must be adequate, and traffic flow impact must be minimized for HV acceptability.

(3) Annual travel patterns of 1978 will remain valid until 1990.

(4) For these patterns, acceptable petroleum-independent or nearly independent mobility in a petroleum-scarce scenario will be required. The 50th percentile annual driving patterns for 1978 were taken as the minimum acceptable petroleum-independent mobility levels.

The HV functional requirements (trip types, daily driving cycles, and annual travel patterns) were then developed. This is called Mission Analysis in the HVA. Based on current vehicle usage patterns and driving cycles, expected mission characteristics for 1990 were analyzed. These data were used to identify the most suitable missions, those that could maximize national petroleum savings. The data were also used to develop daily driving cycles and annual driving patterns to evaluate the petroleum consumption of conceptual vehicles. Because potential petroleum savings of HVs are strongly dependent on driving cycles and patterns, care was used to construct realistic models for simulation. Some trip lengths did not correspond to established driving cycles. For those shorter than the Environmental Protection Agency's (EPA) Urban Cycle (12 km), segments of the Urban Cycle were used to develop schedules. Segments having an end point at zero vehicle speed were selected. Complete cycles, either EPA Urban or Highway, were used whenever the trip lengths permitted.

The HV system requirements (passenger and cargo capacity and performance requirements) were then derived. Nationwide Personal Transportation Study data (1977-1978) provided passenger capacity and trip data. Cargo capacity requirements were estimated by examining conventional vehicles used for similar missions. Performance requirements were estimated from road safety, consumer acceptability, and traffic impact considerations.

The HV design analysis techniques were used to develop alternate vehicle concepts, identify the major characteristics of each concept, select components, size the vehicle, and evaluate energy management strategies. Alternative designs were developed with the requirement that passenger volume, cargo capacity, and interior environmental control accessories be similar to a reference vehicle of identical performance (with respect to speed, acceleration, and gradeability). Common ground rules and consistent comparisons were maintained in analyzing the HTV test results and experience. Using previously developed computer programs (ELVEC and HYVEC IV), vehicle simulations were completed to estimate the petroleum savings potential of each conceptual vehicle. These estimates involved comparing HV petroleum use with that of a reference vehicle having identical performance and driven in the same way. From this process, the most promising HV designs were identified. Results are presented showing:

(1) Petroleum savings per unit reference vehicle petroleum consumption.

(2) Petroleum savings per unit total mission energy.

(3) Petroleum savings per unit vehicle mass.

These are functions of the basic vehicle design parameters, configuration, energy management strategy, and battery mass fraction. The HV use time period for this study was assumed to be the 1990s.

The final step in the HVA was an analysis of the sensitivity of vehicle petroleum savings to changes in design parameters, characteristics, and performance requirements. This determined elements of the design which are most influential in attaining program objectives. Vehicle performance analysis was used along with HTV performance data to evaluate and iterate the design concepts. Vehicle simulation and sensitivity analyses were used, not only to evaluate petroleum savings potential, but also to identify primary and secondary development recommendations. The overall HVA systems analysis methodology is represented in Figure 1.

The designs evaluated in this study were conceptual only. They were not sufficiently detailed to justify the preparation of vehicle production cost estimates. Even though the HVA predictions are near term and based upon relatively certain technology improvements, there is substantial uncertainty in cost prediction. Fabrication, assembly, and materials alternatives exist for mass production designs, which would introduce another level of uncertainty into any cost prediction model. Follow-on studies, including cost analysis, are planned. Recognizing this, the HVA lists promising HV alternatives in order of preference for petroleum savings and does not eliminate any reasonable configuration from consideration. Also excluded from detailed consideration in this report are issues of HV environmental impact, aftermarket and infrastructure requirements, and electrical utility impacts.

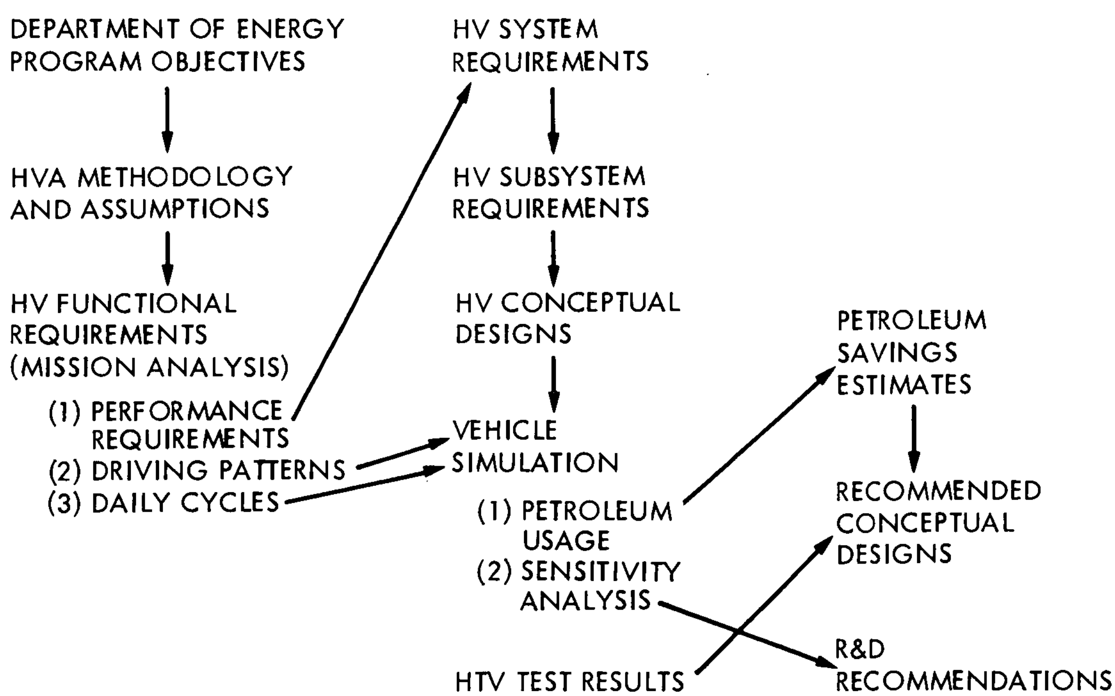


Figure 1. Overall Hybrid Vehicle Assessment Systems Analysis Methodology

CONCLUSIONS

This section contains a compendium of conclusions and recommendations of the HVA. It is intended to furnish a summary without providing extensive explanation, analytical details, or supporting information. If amplifying materials are desired, the reader should refer to the body of the report. It is important to understand that these conclusions are based on petroleum savings computations and not on cost or economic analysis. Such considerations will modify the results of this study, and the follow-on cost analysis will be the final discriminator.

General

Hybrid Vehicles offer a near-term method of introducing electric drive into the U.S. transportation fleet without incurring the limitations imposed by present-day traction battery technology in all-electric applications. In properly designed HVs, both traction subsystems work together to provide petroleum savings with full vehicle performance and acceptable non-refueled range.

Hybrid Vehicles can provide substantial mobility during petroleum shortages. Noise reduction and emission improvements over conventional vehicles are also available but are considered secondary benefits.

Hybrid Vehicles can conserve petroleum, but they are not energy savers in all applications. Total energy expended per mission is frequently less for conventional vehicles than for hybrids.

Analysis of the sensitivity of HV petroleum savings to design and performance parameters as well as basic design trade-offs can be vectorially represented in specific-energy, specific-power coordinates. This representation is useful in visualizing the competing factors that must be considered in any successful HV design.

Missions

Figure 2 shows U.S. fleet mileage estimates by mission. The most attractive petroleum savings applications for HVs seem to be four- and five-passenger general-purpose vehicles. Because of the severely limited volume available for a hybrid power train and batteries in the four-passenger car, it is not an attractive candidate for hybridization. The five-passenger car is preferred.

Figure 3 shows daily driving statistics for the 75th percentile (22, 176 km) four- and five-passenger general-purpose mission, the most attractive mission for national petroleum savings. A hybrid vehicle with an electric range of 160 km could offer 50 to 70% petroleum savings for this mission while satisfying over 90% of daily driving demands for 75th percentile driving patterns.

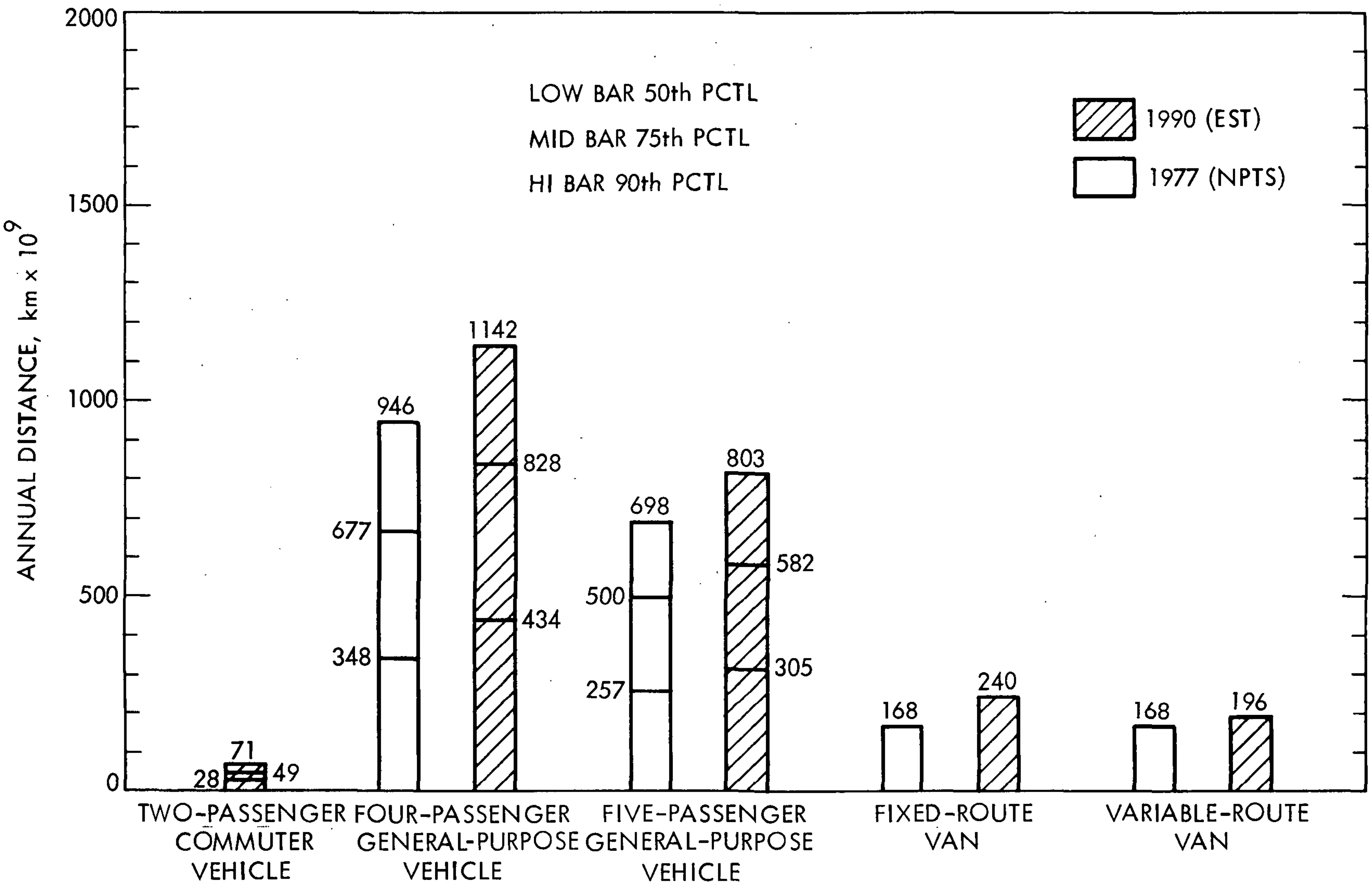


Figure 2. United States Fleet Mileage Estimates by Mission

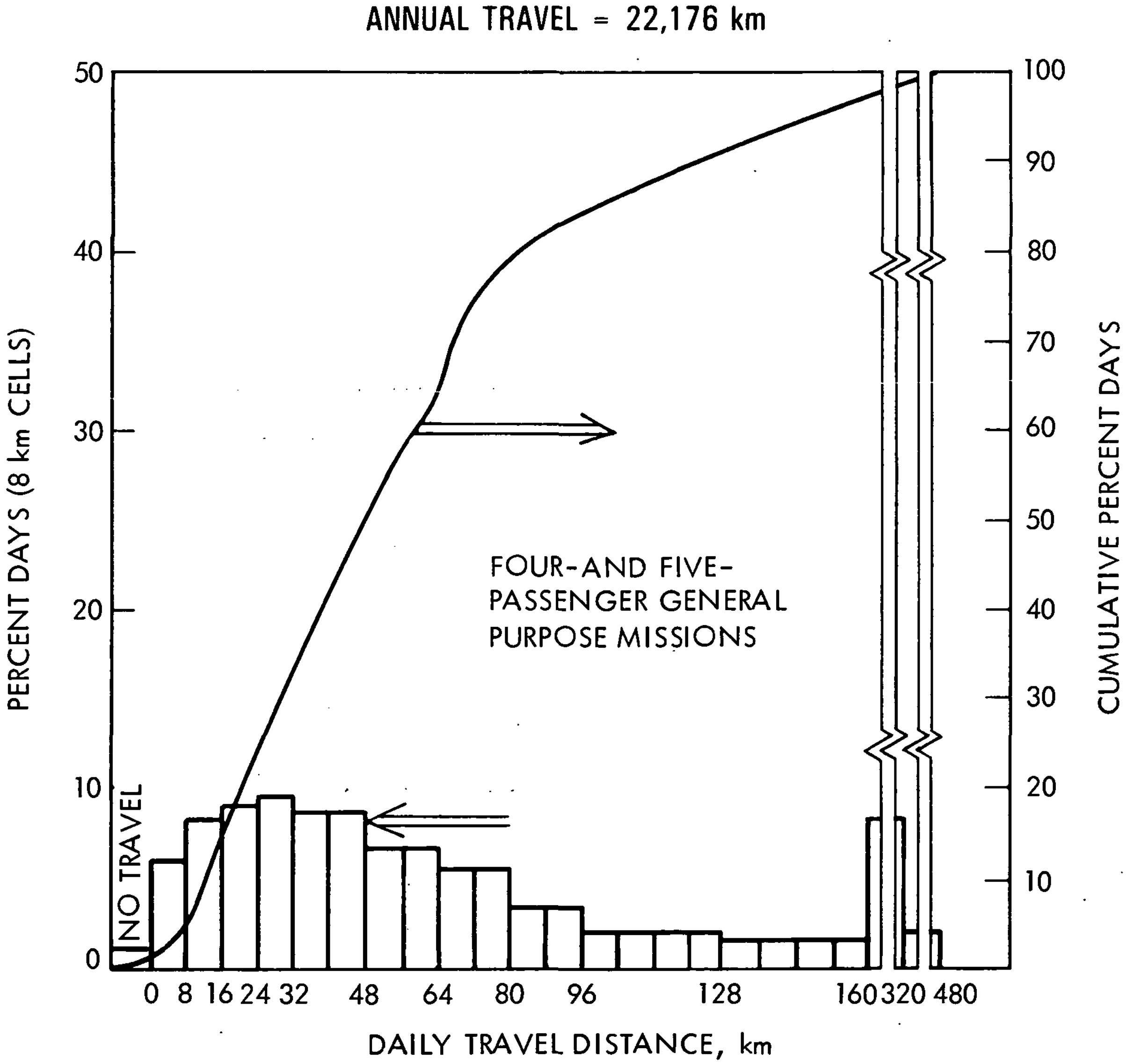


Figure 3. Annual Travel Pattern

Potential petroleum savings are strongly dependent on driving distance. For distances below the 50th percentile, required heat engine use is too low, and a limited range electric vehicle may be superior to the hybrid vehicle for petroleum savings. For 90th percentile driving patterns, the excessive heat engine use compromises petroleum savings. The best annual patterns seem to lie between 50th and 90th percentiles (12,000 km and 30,000 km, respectively).

Not all driving cycles or missions are suitable for HVs. There are missions in which hybrids can actually waste petroleum rather than save it, and petroleum savings estimates are strongly dependent on driving patterns. The two-passenger commuter mission seems more suitable for the electric vehicle than the HV because of the limited range required of the vehicle. (Its petroleum savings potential is also quite limited because of the small fleet size.) The four-passenger vehicle, although offering potential for large national petroleum savings, imposes severe limitations on the volume available for batteries. It is not recommended for near-term hybridization. Van hybridization seems to offer little advantage except for the large-volume availability for experimental development.

Design Analysis

A general method has been developed for the analysis and design of HV energy management and petroleum savings. This involves plotting vehicle requirements and battery capabilities in specific power, specific energy coordinates. Batteries can then be assessed for vehicle-mission suitability, and deficiencies can be vectorially represented. This vector has specific power and energy components. The size of each component then dictates the most appropriate energy management strategy, and the petroleum savings potential of the vehicle can be estimated by computer simulation. Although in the HVA this method was restricted to hybrid vehicles with two energy sources, it can easily be extended to multiple-source propulsion systems.

Hybrid vehicle configuration is the physical arrangement of vehicle subsystems. Because they blend two power sources, they can be configured in two basic ways, series and parallel. Neither configuration by itself, however, dictates the logic by which power is applied or sequenced (referred to as the energy management strategy), and this distinction is fundamental to understanding HVs. Hybrid vehicle configuration must not be confused with energy management strategy. Neither one implies the other, although certain combinations may be preferable.

Future battery development programs must be based on energy and power requirements derived from system-level considerations and realistic driving cycles, rather than the arbitrary C/3 tests or other similarly unrealistic measurement. Recent work by JPL (Reference 2) has emphasized this requirement and developed the concept of an optimum specific-power-to-specific-energy ratio for electric vehicle traction batteries. The optimum ratio is a function of required vehicle range, vehicle weight, aerodynamics, type of driving (urban or highway), and required acceleration performance. The analytical techniques were developed for electrical vehicles, but have been

extended and modified to apply to HVs as well. The logic, when reversed, becomes a design method for vehicles using traction batteries in which the specific-power-to-specific-energy ratio departs from the optimum. In such cases, the heat engine is sized to supply the battery deficiency, with corrections made for the added engine weight and required vehicle modifications.

For each HV conceptual design and driving pattern, a range of battery mass fractions (BMFs) exists in which the battery can supply adequate power and energy, and for which the vehicle mass and size are reasonable. The optimum case is found by varying the BMF and computing petroleum saved in actual driving patterns for each level. Specific utility functions are taken into consideration as part of this analysis.

Hybrid vehicle petroleum savings are presented in three different forms: (1) petroleum savings per unit of petroleum used by the reference vehicle (PS/RVF), (2) petroleum savings per unit HV curb mass (PS/M), and (3) petroleum savings per unit HV total source energy (PS/TE). The first form permits the ready comparison of the percent of fuel saved (or wasted); the others offer two utility functions (and a corresponding range for optimum BMF).

Configurations

For the five-passenger HV, the series/parallel configuration offers the best petroleum savings, with the rear motor parallel a close second. Figures 4 and 5 show these conceptual designs and Table 1 gives their key parameters. Conceptual designs of other vehicle configurations studied include front motor parallel and series configurations, both with lower petroleum savings.

Batteries

The traction battery is the single HV subsystem most in need of experimental development. Battery parameters exerting first-order effects on HV performance are specific power (W/kg) and specific energy (Wh/kg). They enter the power and energy equations through their mass effects. Battery power density and energy density enter vehicle design through their volume effects. Hybrid vehicle design must consider both mass and volume, creating a design "window." Goals of 80 Wh/kg at or below specific power levels of 100 W/kg are recommended for traction batteries with long life at high depths of discharge (typically 90%). These goals are not based on specific battery discharge rate, but rather on the daily cycles, annual patterns, and speed-time profiles used in this analysis. They are appropriate for HVs designed for petroleum savings and should be regarded in that light. Electric vehicle batteries and batteries for HV designs that are affected by cost considerations are expected to be somewhat different.

Hybrid vehicle electric range is determined primarily by battery-specific energy. This is an important difference between electric vehicles and hybrid vehicles. Electric vehicle range is determined by battery-specific power-to-specific-energy ratio, vehicle speed-time profile, and vehicle speed-load

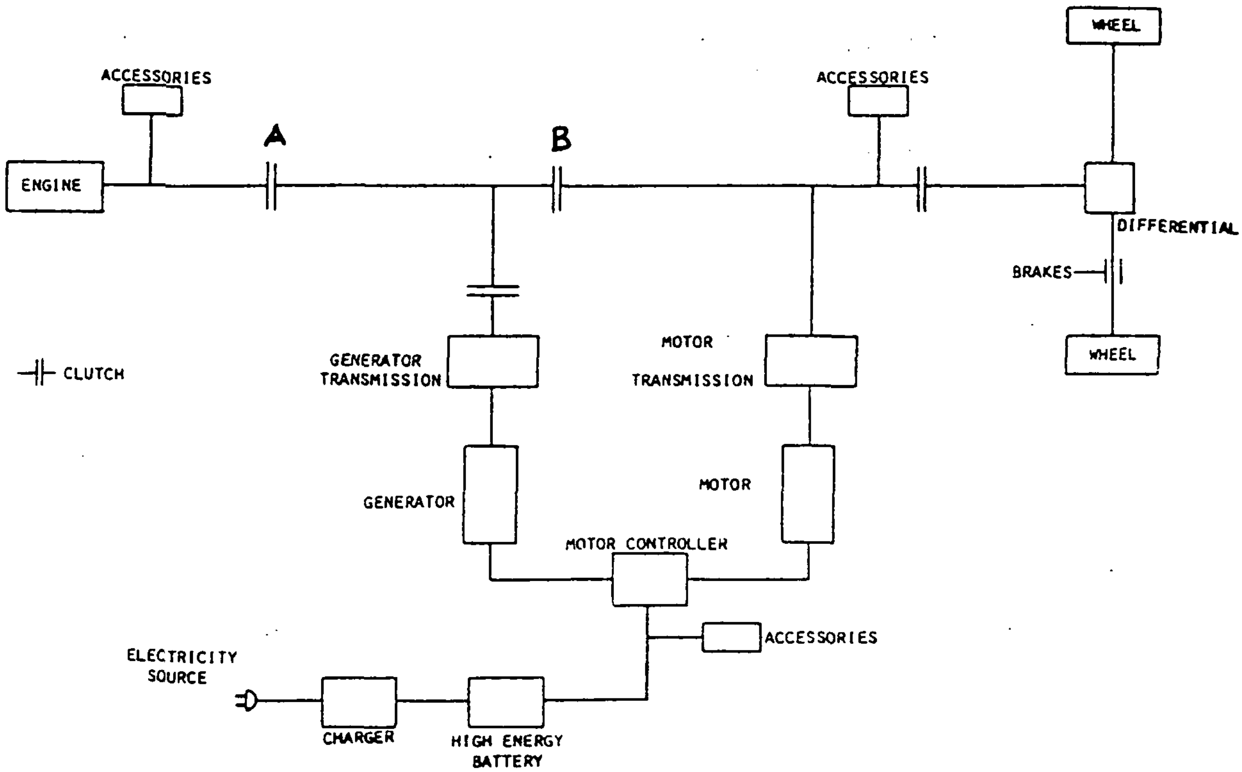


Figure 4. Series/Parallel

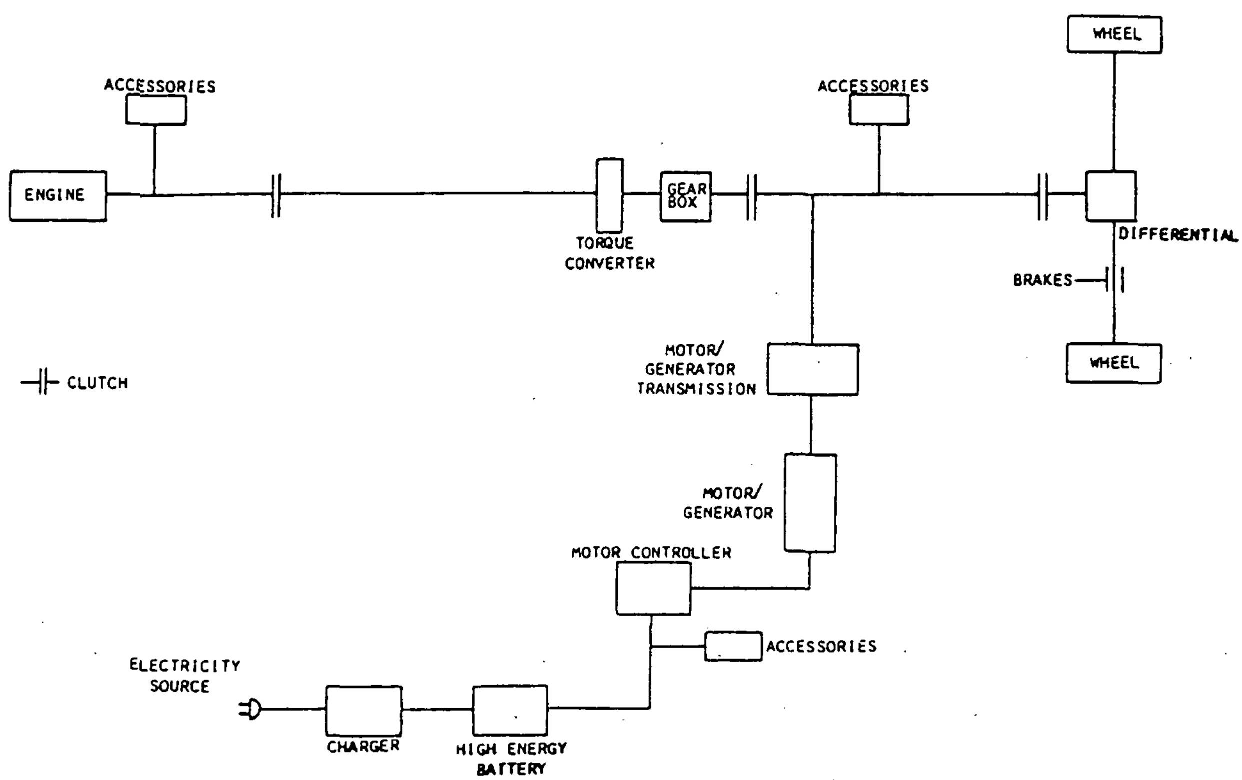


Figure 5. Rear Motor Parallel

Table 1. Series/Parallel and Rear Motor Parallel Five-Passenger General-Purpose HV, Peaking Strategy Key Design Parameters

Parameter	Series/Parallel	Rear Motor Parallel
Total vehicle mass, kg	1502	1451
Chassis mass, kg	763	763
Engine mass, kg	82	88
Engine peak power, kW	25.1	27.6
Motor mass, kg	45	36
Motor peak power, kW	16.9	13.7
Battery mass, kg	273	263
Battery mass fraction	0.20	0.20
Battery type	NiZn	NiZn

characteristics. In the HV range equation, the power-to-energy ratio is replaced by a more complex function involving the vehicle's energy management algorithm, because in HVs electric and conventional power can share the total load. There is, nevertheless, an optimum power-to-energy ratio for the battery for each HV design. If the HV battery is relatively under-energized, the heat engine and fuel system must supply the energy necessary for the vehicle to reach its design range. If the battery is relatively underpowered, the heat engine and fuel system are required to supply the acceleration and (possibly) cruise power deficiencies. For each vehicle design, performance weight, aerodynamic drag, and rolling resistance, there is an optimum specific-power-to-specific-energy ratio that maximizes the petroleum saved by the vehicle when compared to a conventional vehicle driven in the same manner. If this battery ratio departs from the optimum, there will be a petroleum penalty resulting in fuel consumed by the heat engine to correct the mismatch.

For the five-passenger vehicle, petroleum savings estimates are strong functions of battery-specific energy, with near-linear proportionality between 45 and 110 Wh/kg. Optimum HV battery mass fraction is a strong function of specific power. Figures 6 and 7 shows the effects.

The development of high depth-of-discharge (DoD) batteries offers the greatest single petroleum-saving potential analyzed. Continuing battery development is required to correct this deficiency, and a primary development

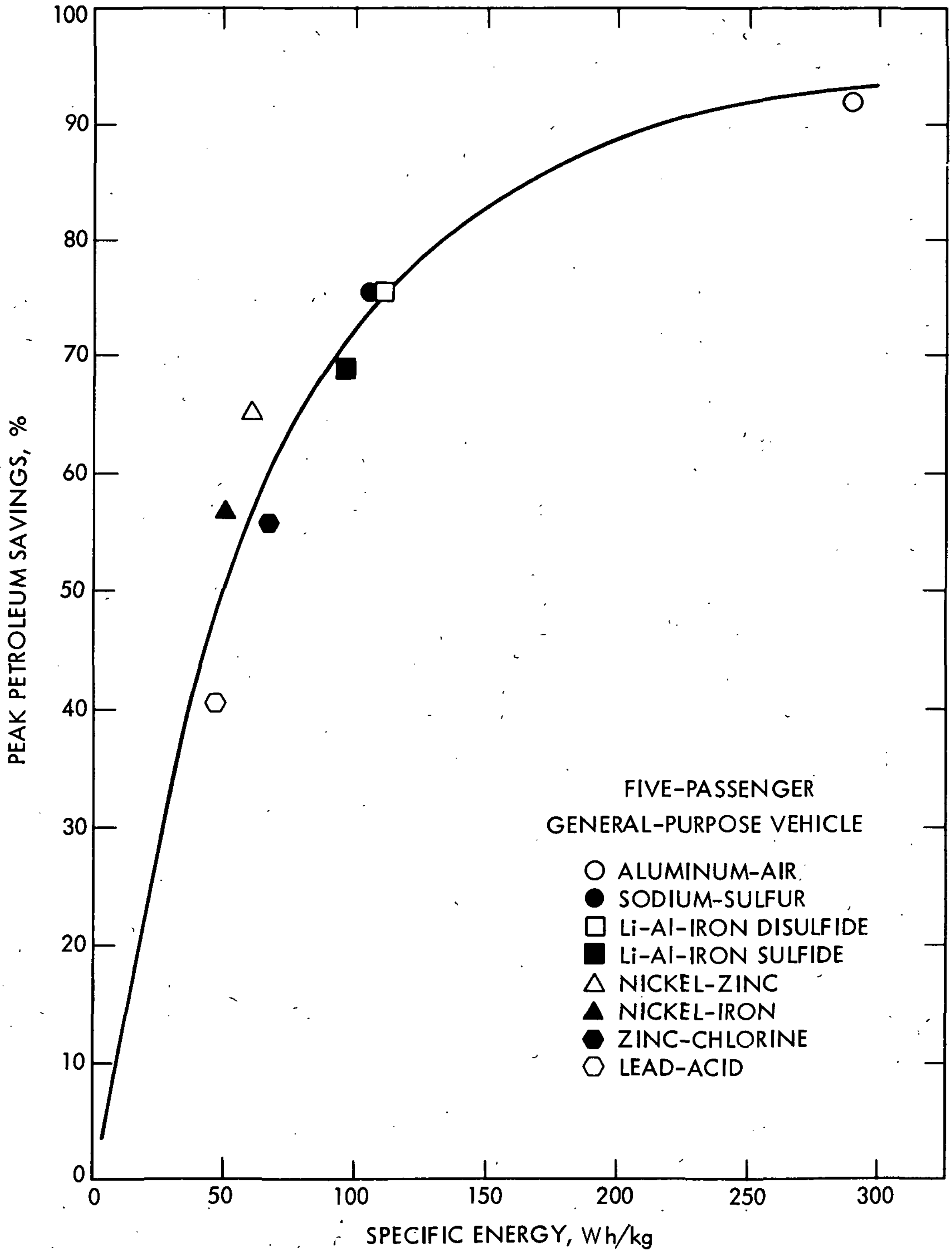


Figure 6. Peak Petroleum Savings for Specific Energy

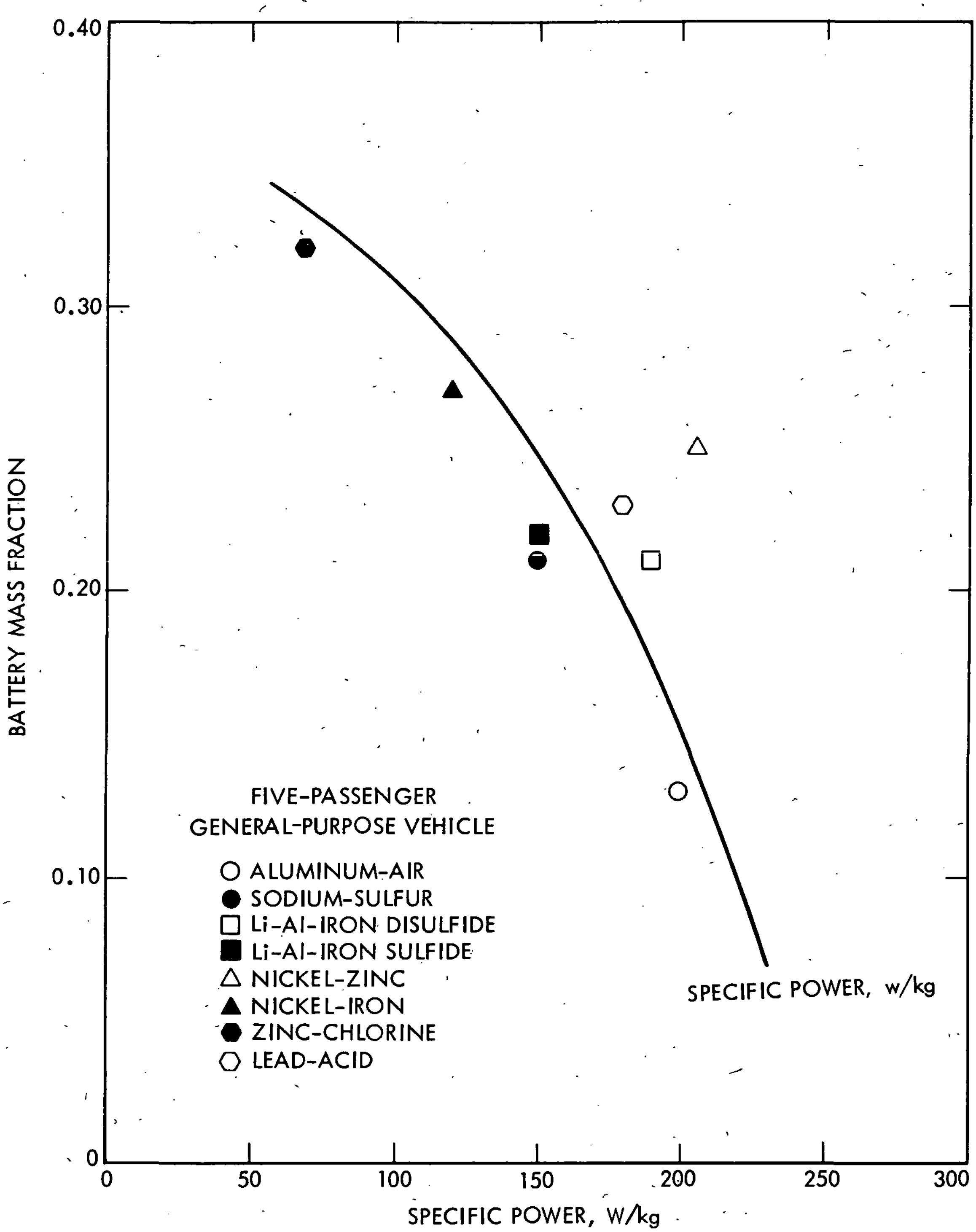


Figure 7. Battery Mass Fraction for System Specific Power

recommendation is made. This is also true for battery specific energy improvement which seems to be unimportant for peaking strategies, except in the case of batteries that are strongly affected by DoD.

The ideal HV battery has high enough specific power over the full state-of-charge range to keep the battery always in an energy-limited state. This combination of energy and power results in the lightest car and, therefore, in the greatest petroleum savings. The hybrid vehicle allows the use of batteries with specific power and specific energy characteristics not suitable for electric vehicles, while still producing significant petroleum savings. This makes the Ni-Zn battery a good HV battery for the near term. Regardless of the specific battery couple employed, an acceptable specific energy of 80 Wh/kg at or below a specific power level of 100 W/kg is a reasonable development goal for hybrid batteries.

Energy Management Strategies

Given any HV configuration, traction battery, and mission, there is an energy management strategy that maximizes the petroleum savings of the vehicle. This strategy is indicated by the relative separation of the battery-capability curve and the vehicle requirements curve in specific power, specific energy coordinates.

For virtually all projected traction battery characteristics and vehicle requirements, the peaking strategy with its high battery utilization offers maximum petroleum savings without excessive energy management system complexity. The least attractive strategy is sharing. The either/or strategy yielded intermediate petroleum savings. Table 2 compares the strategies

Table 2. Summary of the Energy Management Strategy Study for the Five-Passenger Hybrid Vehicle

Configuration	Either/Or, %	Peaking, %	Sharing, %
Series	0.30[a]	0.52	-0.02
Series/Parallel	0.38	0.72	0.48
Front Motor Parallel	0.35	0.48	0.22
Rear Motor Parallel	0.35	0.66	0.43

[a]0.30 indicates 30% of the petroleum consumed by a comparable reference vehicle (Otto cycle engine) is saved by this HV. A negative sign indicates more petroleum is consumed by the HV than by the reference vehicle.

examined for the five-passenger vehicle. Figures 8 and 9 show typical petroleum savings vs battery mass fraction curves.

Testing and Data Acquisition

Lessons learned during HTV development and HVA simulations must be incorporated into next-generation HVs, and continued development and tests of advanced power trains, batteries, and motor controllers for electric automobiles are essential.

Procurement of fully driveable vehicles is not considered necessary. Dynamometer testing of power trains combined with computer simulation has proved to be effective and will allow continuing development of the components critical to HV evolution without requiring large investments. Special attention is required for traction batteries, motors (ac and dc), controllers, and transmissions. Interchangeable (floor-mounted) traction batteries could be tested easily when connected to a GE-type "rickshaw"[1] power train with a complete data acquisition and recording system.

Improved battery life models must be developed (cycle life vs depth of discharge, charging condition, thermal management, reconditioning cycles, etc.) to realize the potential benefits of electric drive.

Miscellaneous

The following observations, while not explored in depth, should be taken into consideration in overall Hybrid Vehicle Assessment.

(1) Torque converter size and engine peak power rating greatly affect petroleum savings. They warrant careful trade-off analysis in HV design.

(2) Acceleration requirements and yearly driving distance also have a large effect on petroleum savings. Understanding these HV limitations by users will greatly improve vehicle acceptability.

(3) Regenerative energy recovery is of marginal importance for petroleum savings, but is necessary to provide battery recharge power during normal driving.

---

[1]The GE "rickshaw" was a complete hybrid power train detached from the remainder of the vehicle. It could be easily placed on the dynamometer, and it allowed quick, easy access to the motor engine, transmission, and batteries for testing, troubleshooting, modification, etc.

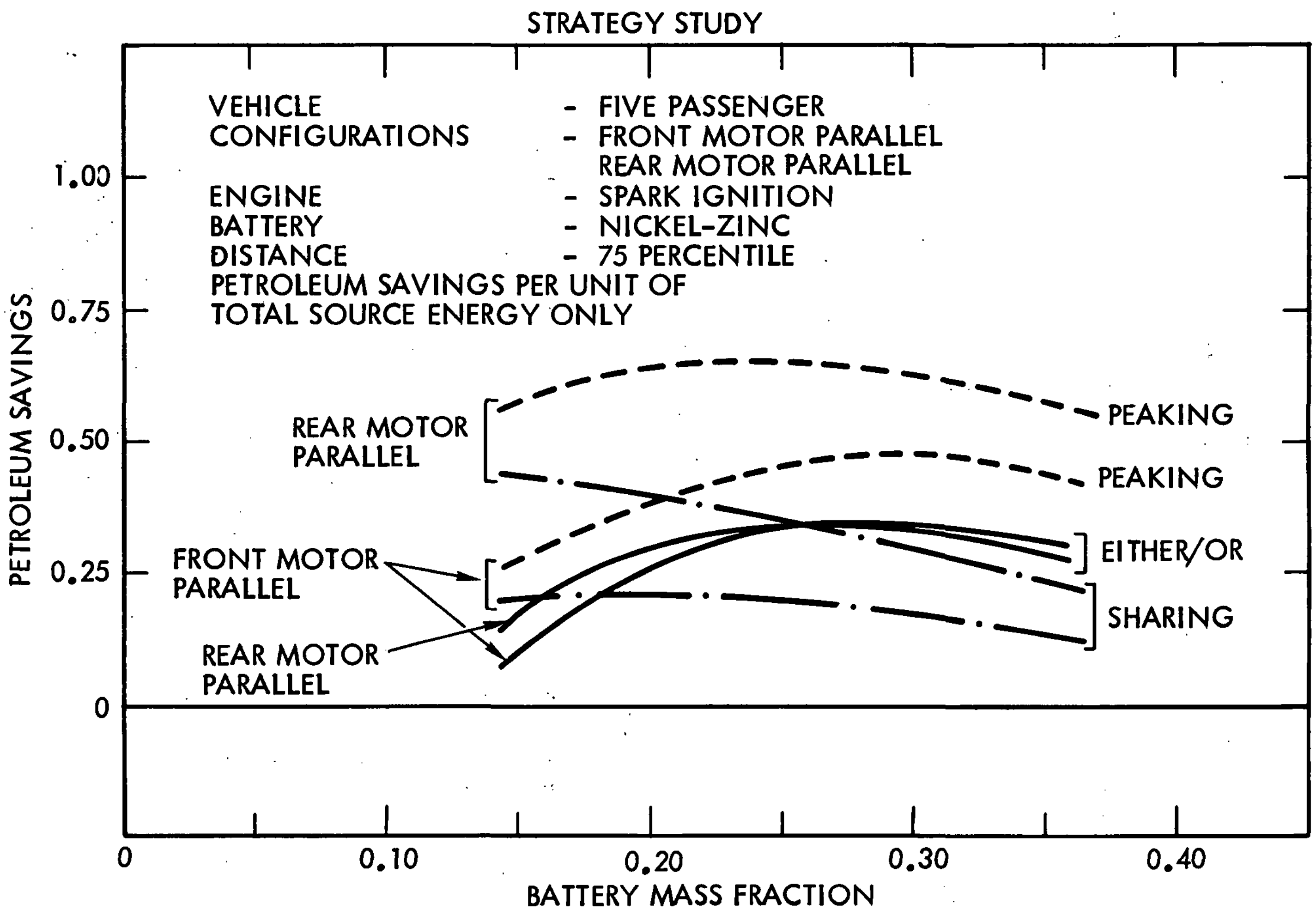


Figure 8. Petroleum Savings for Five-Passenger Vehicle, Front Motor and Rear Motor Parallel Configuration

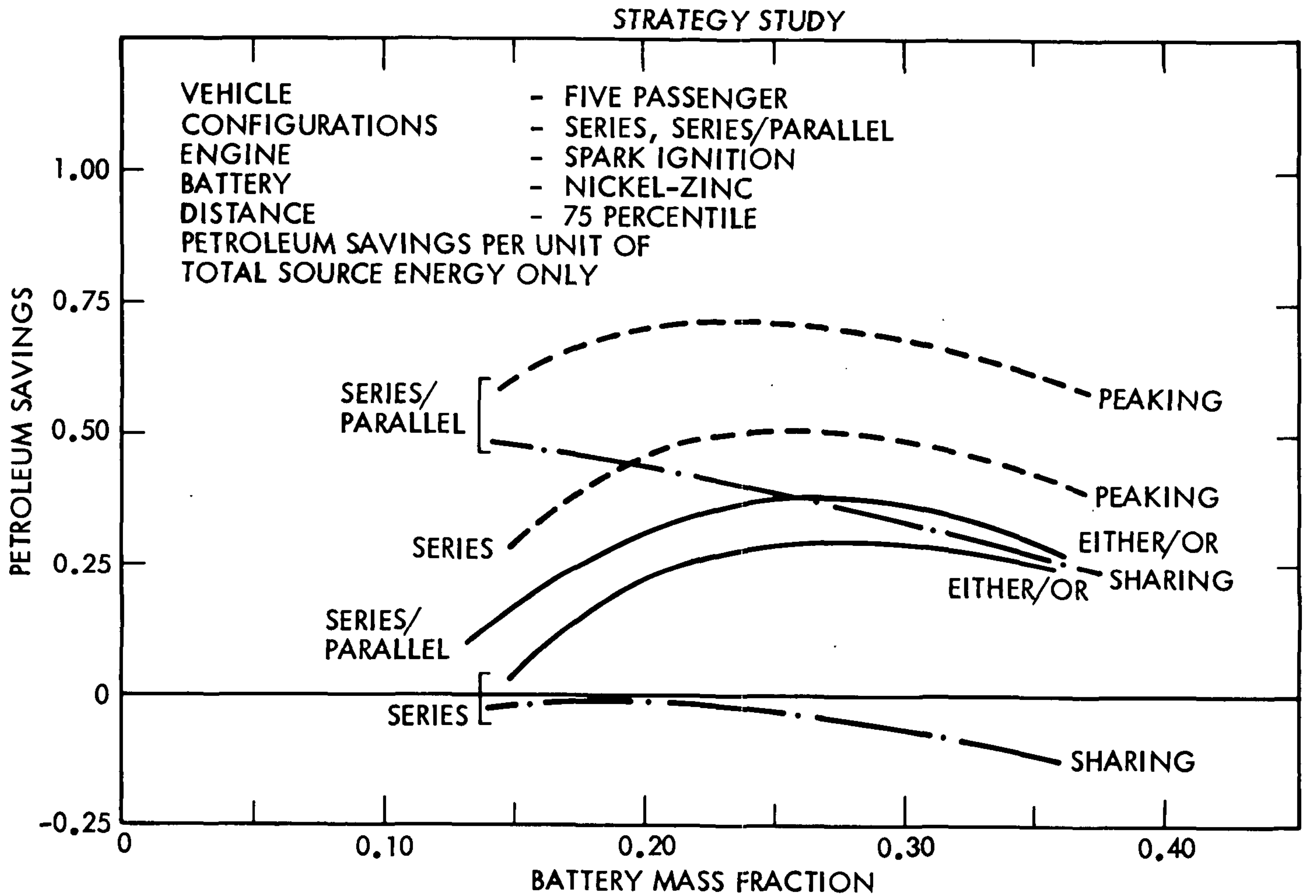


Figure 9. Petroleum Savings for Five-Passenger Vehicle, Series and Series/Parallel Configuration

(4) Weight reduction, transmission efficiency improvement, rolling resistance reduction, and aerodynamic drag reduction are all areas that merit continuing work.

(5) Continuous engine idle imposes almost no penalty on petroleum savings. It does, however, simplify HV power control logic and system complexity. An energy management strategy that idles the engine above the power-limited battery state of charge (SOC) seems to be justified, saving frequent on-off-on operations.

(6) The gate turn-off devices being developed for industrial power control can be useful. Choppers (dc) and inverters (ac) incorporating these devices should be tested for suitability in HV power control.

The General Electric Hybrid Test Vehicle

Testing and evaluation of the General Electric Hybrid Test Vehicle resulted in the following significant conclusions:

(1) The HTV represents a major step forward in the development of HVs. Rapid (400 ms) on-off engine operation, power blending by computer control, and favorable petroleum savings compared to a conventional vehicle were demonstrated. These all represent advances in the state of the art.

(2) Limitations were observed in the performance of the accessory systems. Hydraulic and mechanical losses were higher than expected and substantially compromised HTV performance.

(3) In a parallel configuration, regardless of energy management strategy, the vehicle should be operable from start to stop on either drive subsystem (possibly with degraded performance allowed).

(4) The "rickshaw" concept for power train testing used by GE proved valuable and cost effective. Future HV development programs could benefit from its adoption.

(5) Although substantially heavier than its conventional counterpart, HTV ride and handling were considered very good. The high front-to-rear weight distribution (68:32) presented no rideability problems.

(6) Packaging, component arrangement, and accessibility for maintanance are severe limitations of the HTV design. Smaller devices (higher specific power) and improved (integrated) power trains will yield large volume savings if HV development is continued.

(7) An improved state-of-charge indicator is required for effective battery utilization.

Subsystem Development

The primary HV subsystem requiring continuing development is the traction battery. Its performance, acceptability, and petroleum savings potentially influence the HV more than any other system.

The most serious battery deficiency is specific energy (Wh/kg). Although some petroleum savings can be realized with almost any battery, substantial savings from HVs require appropriate specific energy with specific power deficiencies corrected by proper energy management. Attainable values of 100 to 150 Wh/kg at 120 W/kg over actual driving cycles are required for expected electric vehicle operations. The HV operations with acceptable petroleum savings suggest values of 80 Wh/kg at or below 100 W/kg with deficiencies corrected by heat engine operation. Reductions in specific energy will mean reduced petroleum savings. Typical depths of discharge of 90% are required for effective battery utilization. Cycle life requirements will be determined by subsequent cost analysis.

Development of suitable batteries must proceed in the system context to ensure acceptable:

(1) Throughput efficiencies.

(2) Specific power-to-energy relationships.

(3) Power density-to-energy density relationships.

(4) Cycle life.

(5) Design for deep discharge.

Items (2) and (3) are discussed in this report; items (1), (4), and (5) will be treated in the subsequent cost analysis.

Another class of subsystems requiring development is vehicle accessories (pumps, fans, etc.). Considerable energy and petroleum can be saved by sensing demand and controlling power. This conclusion is not limited to HVs, but will provide more benefit for them than for conventional vehicles.

RECOMMENDATIONS

Continued HV development is recommended to ensure the availability of the technology if petroleum shortages recur in the United States. A system-level development program is necessary to ensure responsiveness to DOE program goals. In addition to the retention of petroleum savings as a program goal, cost and economic factors must be added to the subsequent HV analysis.

Primary recommendations of the analysis are:

(1) Hybrid Vehicle system development should be continued to ensure the availability of HV technology in the event of national petroleum shortages.

(2) Future battery development programs should be based on energy and power requirements derived from system-level considerations and from realistic HV driving cycles.

(3) Experimental development of batteries for HV applications with high depth of discharge (typically 90%) and long life should be accelerated. Specific energy of 80 Wh/kg should be delivered at or below specific power levels of 100 W/kg.

(4) Advanced power train work should be continued to develop high-reliability, high-efficiency HVs.

(5) Diesel hybrids seem to be the most attractive for the five-passenger hybrid vehicle. They should be considered in future HV design and development programs.

(6) Hybrid vehicle development efforts should be concentrated on the parallel configurations and the peaking strategy.

(7) Improved battery life models should be developed which address the effects of varying depths of discharge, charging conditions, thermal management, etc.

(8) Improved accessory controls should be developed to reduce parasitic losses.

(9) The role of the energy management strategy should be considered in HV design analysis. A system allowing continuous engine idle below the power-critical battery state of charge should be considered to reduce power train complexity and mechanical failures.

Secondary recommendations of the analysis are:

(1) Operator-adaptive energy management strategies can offer a new dimension in vehicle operability. The value and consumer acceptability of this technique should receive attention by the auto industry.

(2) Continued development of gated solid-state power switching devices should be pursued for improved ac power control circuits and chargers.

(3) Future battery development must recognize system-level trade-offs between the conflicting requirements for high specifics (energy/power) and high densities (energy/power).

(4) Reduction efforts in weight, rolling resistance, aerodynamic drag, and accessory power should be continued. These items do not seem to contain any hybrid-unique issues.

Part Two
Assessment

SECTION I

BACKGROUND

The Electric and Hybrid Vehicle (EHV) Program began in 1975 under the Energy Research and Development Administration (ERDA). In 1976 Congress, by passing the Electric and Hybrid Vehicle Research, Development and Demonstration Act, Public Law 94-413, created a program aimed at developing vehicles propelled by externally generated, internally stored electrical energy to reduce U.S. dependence on oil, particularly the politically volatile imported oil. Responsibility for this program was transferred from ERDA to the newly created U.S. Department of Energy (DOE) in 1977, and the JPL EHV System Research and Development (R&D) Project is now a program element of the DOE Division of Electric and Hybrid Vehicles and supports its objectives.

The California Institute of Technology (Caltech) is a private nonprofit educational institution chartered under the laws of the State of California. The Jet Propulsion Laboratory (JPL) is an operating division of Caltech. Under Contract NAS7-918 with the National Aeronautics and Space Administration (NASA), Caltech/JPL performs certain research and development tasks, and other related activities, using facilities provided by the Government. JPL's role in the EHV Program is to manage and conduct system research and development of electric and hybrid vehicles and appropriate supporting technologies.

The Hybrid Vehicle Assessment (HVA) is an individual task within the JPL EHV System R&D Project. The goals of the Hybrid Vehicle Task are the advancement of the state of the art in hybrid vehicles (HVs), the establishment of their functional utility, and the evaluation of candidate hybrid designs for further technology development at the vehicle system level. Together with HV technology development, HVA has been a continuing activity within JPL. The HVA is among the most recent of these activities, which date back to 1975. In August of that year JPL completed an analysis of alternate vehicle engine technology and related vehicle improvements. This study, the Automobile Power Systems Evaluation Study (APSES), assessed the possible benefits of employing alternate auto engines and considered vehicle improvements possible within the following decade. It stirred nationwide interest and provoked responses from a wide variety of organizations.

The next HV analytical effort at JPL was the Hybrid Vehicle Potential Assessment of 1980. Primary purposes were the assessment of the potential of HVs to replace conventional Otto- or diesel-powered vehicles within the period from 2000 to 2010, and determination of the technical and economic feasibility of HV designs. Its secondary purposes were assessments of whether HV economic potential and petroleum displacement potential would warrant major expenditures of R&D funds and, if so, identification of the critical technical areas in which R&D could be most usefully concentrated.

The Hybrid Vehicle Potential Assessment reported on the availability of various HV designs and control strategies for the six vehicle missions were

identified and analyzed. Petroleum savings were calculated on the basis of the fleet size projected for the period of interest. Its major conclusions were as follows (Reference 3).

(1) Hybrid vehicles have a maximum potential to replace over 80% of the petroleum used by cars and light trucks with electricity by the year 2010.

(2) The minimum estimated cost of a conversion to such hybrid vehicles would be roughly equivalent to paying $3/gal for gasoline in 1978 dollars. Considerable improvement in battery and controller costs and vehicle mass production are both required to achieve this figure.

(3) Hybrid vehicle costs and the petroleum displacement they provide are directly proportional. The greater fuel displacement by HVs, the greater the cost of displacement. Hybrid vehicles could conceivably replace 40% of the petroleum used by cars and light trucks with electricity by the year 2010 at a cost roughly equivalent to paying $2/gal for gasoline. These vehicles would have smaller battery packs and about half the electric range of the vehicles that would provide 80% as in item (1) above.

(4) No loss of mobility need be suffered by the American public in this conversion. Hybrid vehicles can offer the same payload capacities, performance, range, style, comfort, and amenities as today's cars and trucks if properly designed and executed.

(5) The ultimate potential of HVs as a viable substitute for the conventional internal combustion engine (ICE) vehicle will be limited not by technology but by high initial and life-cycle cost. Present hardware is adequate in terms of physical parameters, but considerable cost reductions are required.

(6) The critical technical areas where R&D money can be most usefully spent are:

    (a) System design and development. It remains to be shown that the designs in this study or similar ones can be built in mass producible, driveable forms.

    (b) Development of low-cost, long-lived batteries, even at the expense of specific power and specific energy.

    (c) Development of low-cost controllers.

At the present time three HV activities are ongoing at JPL, each oriented toward a different time period. Development and testing of the HTV, the near-term activity, resulted in delivery of the last of three vehicles in April 1983. The objective of this project was the demonstration and evaluation of an experimental integrated power train using both an internal combustion engine and an electric motor. This project is described in detail in General Electric Hybrid Test Vehicle (GE HTV) documentation and is briefly

summarized in this report. The second activity is the HVA. It is a near-term study with an assumed period circa 1990. The third activity is the Advanced Vehicle System Assessment. This study is an analysis of the capabilities of personal vehicles using non-petroleum fuels beyond 1990. Its objective is to recommend research priorities for advanced non-petroleum-based vehicles, targeting technology readiness in the early 1990s and commercialization by industry in the late 1990s.

This report describes the HVA conducted by the JPL Electric and Hybrid Vehicle Project during the period from October 1981 to September 1983. The purposes of the study were to:

(1) Understand the general design requirements of HVs.

(2) Understand the attributes and petroleum savings capabilities of HVs.

(3) Identify the most appropriate missions for HVs.

(4) Summarize the lessons learned during the HTV Program.

(5) Recommend for further development those HV configurations and subsystems which offer the greatest promise for improving the potential of HVs as petroleum savers for the U.S. transportation fleet.

To meet this last purpose, petroleum savings must be substantial enough to justify the expenditure of the required R&D funds. This will ultimately require a cost analysis of HVs to complement this petroleum savings analysis.

In every case analyzed, the DOE program goal of national petroleum savings was foremost. It is recognized, however, that U.S. automobile industry perspectives are somewhat different, being based on marketing strategies and consumer acceptance rather than on national petroleum savings. This may result in differing conclusions between DOE-funded programs and those of industry. At this stage of HV development, however, such differences need not be cause for serious disagreement. Hybrid vehicles will compete with the conventional car to some degree; they will also be complementary to conventional cars and find a place in the national transportation fleet on their own merit. When the missions were examined, it became clear that the range limitations of present HV designs need not compromise their usefulness. According to the 1977-to-1978 nationwide Personal Transportation Study, some 96% of all U.S. automobile trips are less than 48 km and some 98% are less than 80 km. A 30-km range is within the design envelope of the GE HTV now being tested at JPL. Next-generation design will improve not only the electric range of HVs but other performance parameters as well, and a 98th range percentile vehicle is expected to be within its capability. The potential for national petroleum savings by such vehicles is impressive.

It is also recognized that there is an industry reluctance to pursue HV system design activity for several other reasons:

(1) Industry has not clearly identified a market for HVs.

(2) Industry has not seen indications of propulsion subsystem technical readiness.

(3) Industry does not view the HV as a competitor with the conventional car.

(4) Industry recognizes that changes to the supporting infrastructure would be required.

The DOE EHV Program is able to take a longer-range view of the U.S. mobility fuel picture. It can provide an impetus toward national petroleum savings in anticipation of a scenario in which the HV will be needed and the required development time may be unavailable.

The future price and availability of mobility fuels in the United States have been the subject of much speculation. Economists, historians, and political scientists are far from agreement on price, availability, and market conditions, even in the relatively near term. The differential escalation rates (price rise in real dollars over inflation) of mobility fuels is subject to the laws of the marketplace, i.e., supply vs demand. The effects of the recent encouragement of new exploration, political instabilities in the Middle East, and related uncertainties make predictions difficult. Superimposed on this set of issues, however, are the effects of various governmental policies, at this point largely unknown. Subsidies, taxes, import quotas, and import taxes further complicate an already difficult picture.

Several possible scenarios exist, but there are some potentially common factors in each of them:

(1) The United States may face future shortages of mobility fuels such as occurred in 1973, when oil flow from the Middle East was reduced by some 5%.

(2) The emplacement of the Strategic Petrolem Reserve will mean that any shortage must be of long duration to be significant.

(3) Future disruptions will probably occur with little advance warning.

(4) If such long-duration disruptions occur, they will cause major perturbations in U.S. travel patterns and near-term solutions will be needed.

(5) Preservation of even limited mobility will be more important than cost-related or price-related factors in petroleum consumption.

It is important to understand that the HVA was a near-term analysis activity. It was assumed that the vehicle subsystems evaluated were either available now or would be available by the year 1990. The HV evaluation based on alternate fuels was also eliminated from consideration for this reason.

The HV Mission Analysis and Performance Requirements Analysis are timed for the 1990s, and HV conceptual design and recommendations for subsystem engineering development are timed for the near term. This timing difference is not an inconsistency. If market entry is to occur in an orderly fashion, the required engineering development must precede it. A near-term development

program for initial HV technology is required if system technical readiness is to occur in the 1990s. High-priority development items are therefore identified for near-term pursuit.

Such analyses begin with program objectives. These are used to establish a methodology which, when combined with the necessary assumptions, can generate a set of functional requirements. From these, two lower levels of detail are generated, a vehicle system and subsystem requirements. From these structured requirements, conceptual vehicle designs can be generated with traceable properties. When the evaluation criteria developed from program objectives and functional requirements have been assembled, the conceptual vehicle designs can be evaluated and ranked. The results will then be compatible with overall DOE program objectives.

The overall HVA systems analysis methodology is shown in Figure 1-1. Petroleum savings shown represent the yearly difference in petroleum consumption between the reference vehicle (heat engine only) and the conceptual HV driven in the same annual pattern, both vehicles having identical performance.

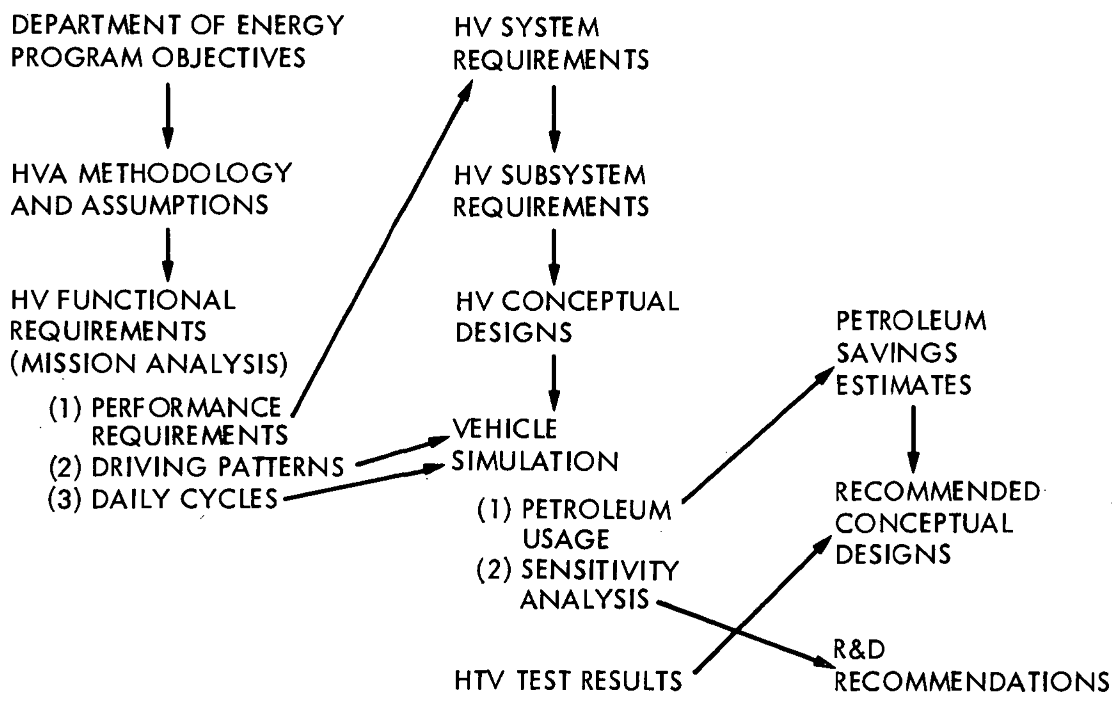


Figure 1-1. Overall Hybrid Vehicle Assessment Analysis Methodology

As the assessment was a "top-down" system-level activity, it began with an examination of the DOE program objectives that promote national petroleum savings. Required next was development of the HVA methodology and assumptions. These were:

(1) Future mobility fuel (petrochemical) shortages are likely.

(2) Performance characteristics of successful HVs must match those projected for 1990 conventional vehicles in regard to safety and traffic flow properties.

(3) Annual travel patterns of 1978[1] would remain valid until 1990.

(4) For these patterns, acceptable petroleum-independent or nearly independent mobility in a petroleum-scarce scenario would be required. 50th percentile annual driving patterns were taken as the minimum acceptable petroleum-independent mobility levels.

The HV functional requirements (trip types, daily driving cycles and annual travel patterns) were then developed. This is referred to as Mission Analysis in the HVA. Based on current vehicle usage patterns and driving cycles, expected mission characteristics for 1990 were analyzed. These data were used to identify the most suitable missions, those which could maximize national petroleum savings. They were also used to develop daily driving cycles and annual driving patterns which could be used to evaluate the petroleum consumption of conceptual vehicles.

From these, HV system requirements (passenger and cargo capacity and performance requirements) were derived. Nationwide Personal Transportation Study data (1977-1978) provided passenger capacity and trip data. Cargo capacity requirements were estimated by examining similar conventional vehicles. Performance requirements were estimated from road safety, consumer acceptability, and traffic impact considerations. The methodology for establishing HV performance requirements was developed during the JPL Hybrid Vehicle Potential Assessment and was used in the HVA as well. Actual performance requirements are somewhat different, but the same methodology for their derivation was used.

The next step in the HVA was the division of the HV into its basic subsystems (controls, energy storage, and propulsion). Alternative conceptual designs were developed that were capable of meeting the functional and system level requirements.

---

[1] The date listed, 1978, is that of the National Personal Transportation Study on which this report was based. 1990 is the assumed end point of this study.

The HV design analysis techniques were used to develop alternate vehicle concepts, identify the major characteristics of each concept, select components, size the vehicle, and evaluate energy management strategies. The alternative designs required that passenger volume, cargo capacity, and interior environmental control accessories be similar to a reference vehicle of identical performance (speed, acceleration, and gradeability). Consistent comparisons were made and the HTV test results and experience were analyzed. Using previously developed computer programs (ELVEC and HYVEC IV), vehicle simulations were completed to estimate the petroleum savings potential of each conceptual vehicle.

These estimates were made by comparing HV petroleum usage with that of a reference vehicle with identical performance driven in the same way. From this process the most promising HV designs were identified.

The next step in the HVA was an analysis of the sensitivity of vehicle petroleum savings to changes in design parameters, characteristics, and performance requirements. This determined those elements of the design which most influence the attainment of the program objectives. Vehicle performance analysis was used along with HTV performance data to evaluate and iterate the design concepts.

Vehicle simulation and sensitivity analyses were used, not only to evaluate petroleum savings potential, but also to identify primary and secondary development recommendations. The results of the sensitivity analysis appear in the Section V. The process occurred as shown in Figure 1-2.

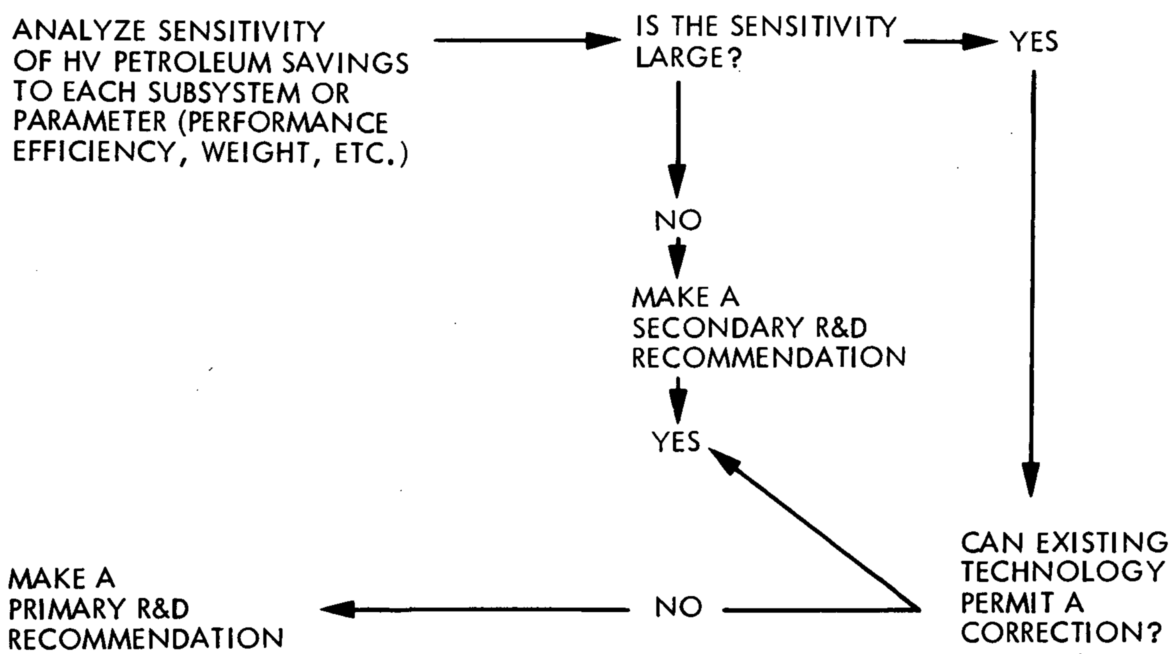


Figure 1-2. Analysis of Sensitivity of Hybrid Vehicle Petroleum Savings to Each Subsystem or Parameter

SECTION II

METHODOLOGY

A. THE HYBRID VEHICLE ANALYSIS

The HVA was planned and accomplished as a system-level assessment of HVs. It was coordinated with a similar and concurrent JPL system-level assessment of advanced vehicles. There were seven major objectives of the assessment:

(1) To understand the attributes of hybrid vehicles.

(2) To develop a general methodology for understanding HVs and their design parameters.

(3) To identify the most appropriate missions for HVs and develop realistic driving patterns for further use in computer modeling and simulation work; to estimate performance requirements for safe operation, consumer acceptability, and acceptable traffic impact.

(4) To investigate alternative hybrid vehicle configurations (including propulsion subsystems, control, energy storage sybsystems) and performance potential assessment of HVs as petroleum savers and as operational vehicles. This includes modeling and simulation of conceptual designs and comparison of actual HTV test data with model prediction and validation techniques for prediction of petroleum consumption, component efficiencies, and vehicle acceleration performance.

(5) To identify critical technologies and develop operating strategies for the most promising HV configurations.

(6) To assess the potential of the most promising hybrid vehicle conceptual designs to reduce U.S. petroleum consumption.

(7) To summarize the lessons learned during construction and test of the GE HTV.

Figure 2-1 shows the strategy followed to analyze potential HV petroleum savings.

Standing somewhat apart from the rest of the report is Section III on HV design and assessment. It describes a method, developed during the HVA, which allows analysis of any HV including roles of electrochemical energy, petrochemical energy, and energy conversion subsystems. Also discussed in this section are HV attributes which are independent of vehicle configuration and, in some cases, independent of the energy management strategy.

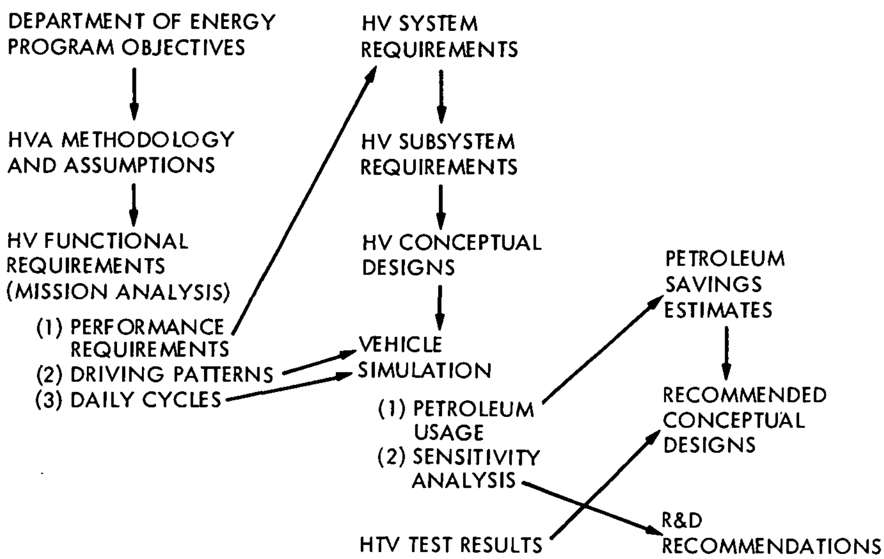


Figure 2-1. Strategy for Analysis of Potential Petroleum Savings

B. PETROLEUM SAVINGS BRACKETS

Introduction of HVs into the U.S. transportation fleet is only one method of saving petroleum. Fleet conversion from Otto to diesel-cycle engines (with perhaps some reduction in vehicle acceleration performance) could yield approximately 15% petroleum savings, chiefly because of the superior part-load efficiency of diesels. These savings could be realized without the introduction of a new large-scale industrial capability such as that required for traction battery manufacture. If HVs are to be seriously considered for widespread fleet introduction, they should offer substantially more than a 15% petroleum saving.

Five percent of all 1990 U.S. electrical energy will be petroleum-produced. Pure electric vehicles would save some 95% of the expected 1990 vehicular petroleum consumption and, therefore, 95% would become the upper limit of possible petroleum savings. Hybrid vehicles should save substantially more than 15% of conventional vehicle petroleum used and will necessarily save less than 95%. This bracket is taken as a derived program requirement for HVs. Analysis shows that savings of 50% can be expected, with 70% possible in some cases.

SECTION III

DESIGN AND ASSESSMENT

A. INTRODUCTION

This section includes a number of issues central to HVs and stands somewhat apart from the remainder of the report because the issues are generally design-independent. A general discussion of HVs is first presented with additional material provided on electrical performance, energy management, HV design analysis, battery mass fraction optimization, utility functions, design optimization, battery characteristics, volume considerations, and miscellaneous issues. This information should be useful when considering the design-specific material further on in the report.

B. GENERAL DISCUSSION OF HYBRID VEHICLES

A hybrid vehicle is a vehicle employing two or more energy storage and conversion subsystems, one of which is a secondary (rechargeable) battery, electric motor, and controller. The preferred second subsystem, by virtue of its superior specific power and specific energy, is a conventional heat engine with a petrochemical fuel system.

The electrical traction subsystem uses electrical energy (coal-generated, nuclear-generated, etc.) instead of premium liquid petrochemical fuels to recharge a secondary (reversible) battery. The electrical subsystem can also permit more favorable engine operating conditions over the wide range of road loads encountered in normal driving, improving the overall fuel economy of the vehicle.

The conventional traction subsystem complements the HV's electrical subsystem by providing part or all of the road load as the battery is discharged. <u>In a properly designed HV, the two traction subsystems work together to provide petroleum savings with full vehicle performance and an acceptable non-refueled range</u>.

Hybrid vehicles, containing two independent energy storage and conversion subsystems, can span the range from conventional vehicle (no petroleum savings) to pure electric vehicle (maximum petroleum savings). Where any HV fits in this range depends on four factors:

(1) Energy management strategy (how and when each energy conversion subsystem is used).

(2) Use of the vehicle with respect to annual distance traveled (low vs high) and type of driving (urban vs highway).

(3) Performance capabilities of the electrochemical drive subsystem.

(4) Vehicle configuration (series, parallel, or series/parallel).

These factors are independent, and petroleum consumption can vary widely, depending on each. They are all treated within the HVA, and the first three are introduced in this section. Vehicle configuration is discussed under Hybrid Vehicle Power Systems.

Energy management is the method of power allocation between electrochemical and petrochemical storage and conversion subsystems. It determines which system is primary, the conditions under which power is shared, switching or crossover conditions between systems, electrochemical energy held in reserve, driver overrides allowed, etc. Energy management strategy is a very important feature of any HV, and considerable attention has been devoted to understanding its ramifications for the vehicles considered.

More than any other component, the traction battery influences the HV. It is fundamentally different from other energy storage subsystems because the amount of extractable energy can be a function of the rate of removal, the power demand, or load. This means that HV performance can be influenced by the energy management strategy and that the performance of the vehicle can influence battery design as well, a classic example of why a system analysis approach to HV design is necessary. With petroleum savings as the goal, the traction battery must be matched to the vehicle (proper engineering design) and to the mission (proper requirements analysis). Neglect of the trade-offs in either direction will require that the heat engine-fuel system correct for any mismatch with greater-than-optimum petroleum consumption.

C. ELECTRICAL PERFORMANCE

For any hybrid vehicle there is an "electric range." It may be described as a distance the HV can travel using its stored electrochemical energy with possible intermittent assistance from the heat engine. It may be an optimum electric range (battery discharged to some preferred depth of discharge, DoD) or a maximum electric range (battery fully depleted). Either description of HV electric range is a strong function of vehicle mass, battery-specific energy (watt-hours per kilogram), driving, cycle (urban or highway), cruise speed, aerodynamic drag, rolling resistance, power train efficiency, and energy management strategy.

Battery-specific energy is the single most important battery parameter affecting electric range. Sometimes overlooked, however, is the effect of battery-specific power. It is the electrochemical power available per unit of battery mass, and it exerts a first-order influence on petroleum savings during vehicle acceleration. A low value of specific power means the stored electrochemical energy must be extracted from the battery at a low rate. The heat engine must supply the power deficiency, often in regions of unfavorable brake specific fuel consumption (BSFC), and inefficient petroleum consumption results. A high specific power permits extraction of stored electrochemical energy at rates favorable to the required road loads and is necessary for full HV performance without undue petroleum penalty.

The HV electric range is determined primarily by battery-specific energy. This is an important difference between electric vehicles and hybrid vehicles. Electric vehicle range is determined by battery-specific-power-to-specific-energy ratio, vehicle speed-time profile, and vehicle speed-load

characteristics. In the HV range equation, the power-to-energy ratio is replaced by a more complex function involving the vehicle's energy management algorithm, because in HVs electric and conventional power can share the total load. There is, nevertheless, an optimum power-to-energy ratio for the HV battery. If the HV battery is relatively under-energized, the heat engine and fuel system must supply the energy necessary for the vehicle to reach its design range. If the battery is relatively underpowered, the heat engine and fuel system are required to supply the acceleration and (possibly) cruise power deficiencies. For fixed performance parameters, vehicle weight, aerodynamic drag, and rolling resistance, there is an optimum specific-power-to-specific-energy ratio which maximizes the petroleum saved by the vehicle when compared to a conventional vehicle driven in the same way. If this battery ratio departs from the optimum, there will be a petroleum penalty appearing as fuel consumed by the heat engine to correct the mismatch. There is, therefore, a balance required between specific power and specific energy, and battery development must proceed with benefit of interaction with HV system developers to ensure that a proper balance between mission requirements and vehicle performance is maintained. This topic is treated in more depth under Design Optimization in this section.

Once the HV has reached its electric range and the batteries are no longer the principal source of energy, it operates very much like a conventional automobile, and the additional range of the vehicle is the remaining range supplied by the heat engine and fuel carried. That energy may be supplied as mechanical energy directly to the vehicle drivetrain (parallel configuration), or it may be supplied as electrical energy to the electric traction subsystem which drives the vehicle (series configuration). Regardless of configuration, the additional vehicle range is determined by the remaining on-board energy (fuel carried) and the efficiency in conversion to tractive energy.

After the batteries are depleted, HV fuel economy will be inferior to a comparable heat engine vehicle. The depleted batteries no longer contribute to petroleum savings but must still be carried. This weight penalizes HV performance, and vehicle missions having ranges that regularly and substantially exceed the electric design range must be classified as inappropriate for HVs. The penalty is excess petroleum consumption which is covered later in this section under Design Analysis.

D. ENERGY MANAGEMENT

Since an HV contains two independent energy storage and conversion systems, the vehicle has the capability to vary the amounts of power drawn from each system according to its energy management strategy. The HV control system is therefore inherently more complex than that of a conventional car. The more complex nature of the HV does not, in itself, make the HV less attractive; however, when that complexity causes high failure rates, frequent repairs, high costs, or excessive downtime, it becomes a liability. The dual power attribute of HVs is advantageous because the near-term limitations of traction battery technology can be minimized and because additional control flexibility is available. Variations in the basic energy management strategy may be made based on battery state of charge, road or terrain conditions, a desire by the driver to save fuel, to minimize emissions, to improve

performance, to limp home after failure of one of the traction systems, or some other strategy.

This adaptive feature is an important and primary attribute of HVs and offers the possibility of building a "programmable" car, a truly versatile vehicle which can employ its two-component power plant in more than one way. Fuel economy, electric economy, performance, cost, and emission control then become objective functions which can be individually optimized, or even scaled, according to the needs of the driver, the terrain, or the mission.

Hybrid vehicle configuration is the physical arrangement of vehicle subsystems. Blending two sources of power, HVs can be configured in two basic ways: series and parallel. Neither of these configurations by itself, however, dictates the logic by which power is applied or sequenced (referred to as the energy management strategy), and this distinction is fundamental to understanding HVs. Configuration must not be confused with energy management strategy. Neither one implies the other, although certain combinations may be preferable. This is discussed in the next part of this section and again in Section V.

There are four basic methods of energy management:

(1) In the either/or strategy, either the electrical system or the heat engine supplies the road load. They never provide power simultaneously. Each system must be capable of supplying full vehicle acceleration and gradeability performance.

(2) In the engine-peaking strategy, the battery-electric motor system supplies all propulsion energy, with possible exceptions during acceleration, until some predetermined battery DoD is reached. At that point, the heat engine may be called on to provide all propulsion energy, or the electric motor and heat engine may share the load.

(3) In the motor-peaking strategy, the heat engine-fuel system supplies all propulsion energy, with possible exceptions during acceleration or on driver command. The electric motor is used as a power peaking device.

(4) In the shared strategy, both heat engine and electric motor supply power simultaneously in proportions determined by the control system logic.

These options are shown in Figure 3-1. They are strategies in themselves and do not depend on how they might be mechanized within the vehicle. The mechanization can range from pure manual control (entirely driver selected) to full automatic control. Items (2) and (3) are considered as a single strategy in this study, described as the peaking strategy. The basic petroleum saver is, of course, engine peaking. Motor peaking is used to extract energy below any state of charge at which the battery is power limited.

Each of these basic energy management strategies has certain attributes (most appropriate battery mass fraction, subsystem sizes, and petroleum savings, for example). Because of weight differences, each of the four

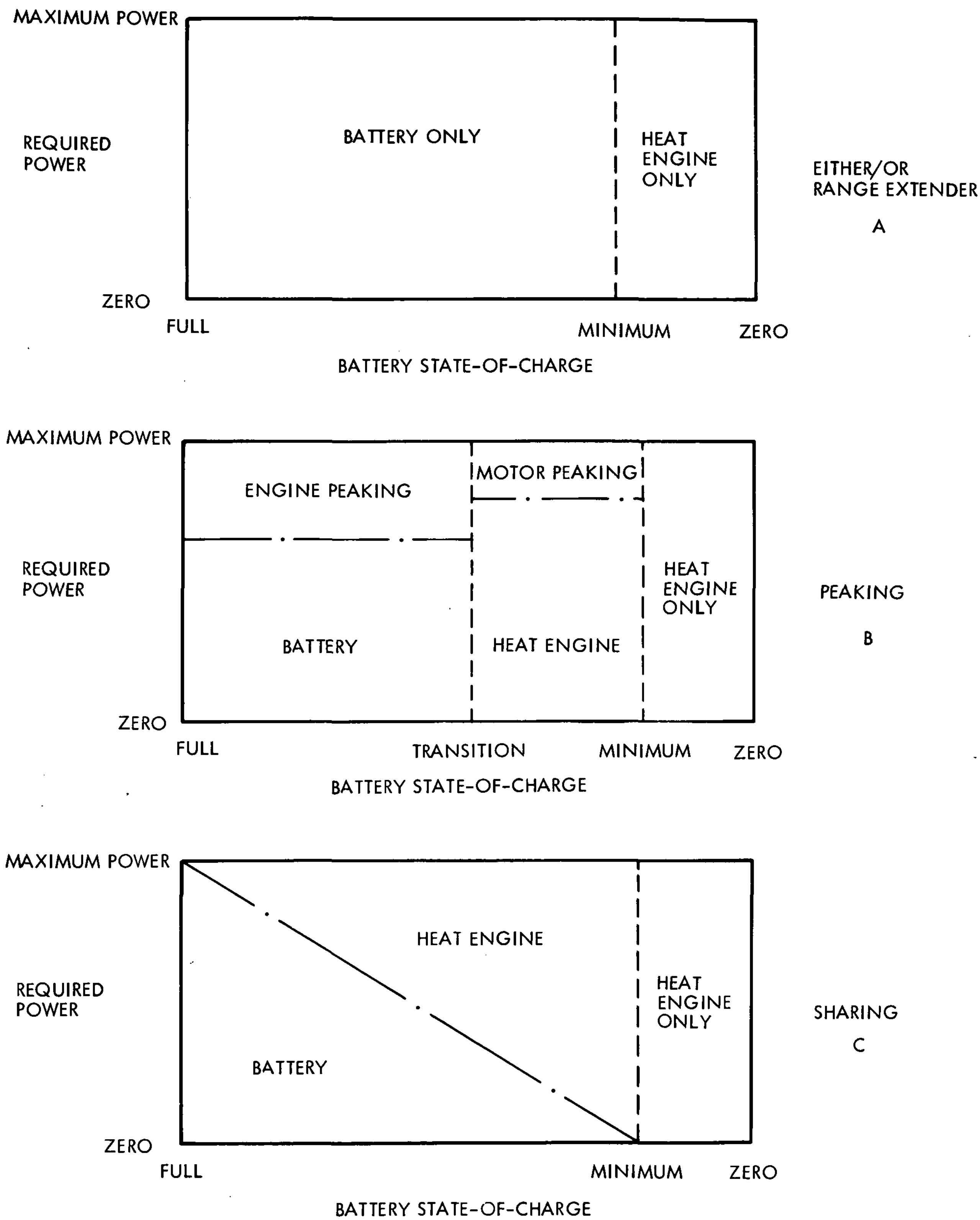


Figure 3-1. Energy Management Strategies

requires different total tractive power as well as different ratios between conventional and electric subsystem ratings. In this study, the required acceleration performance of all vehicles is fixed, configuration and energy management strategy are selected, and an appropriate power train is then sized. Petroleum consumption figures are calculated for each vehicle for common daily driving cycles and annual patterns.

Power train sizing does not always provide unique values for components. There are no simple or universal rules for component sizing; judgment and/or secondary trade-offs are frequently required. Heavier vehicles require larger power trains to provide the required acceleration with resulting decreases in petroleum savings. Properly implemented, the energy management strategy permits the electrochemical and the petrochemical systems to complement each other. The sensitivity of the HV to battery performance can thus be controlled.

E. DESIGN ANALYSIS

With the topic of energy management introduced, the principal issues in HV design and analysis can be discussed and interaction between battery performance and vehicle requirements analyzed. Figure 3-2 is a general battery energy capability curve. It is a plot of battery specific energy available (watt-hours of electrochemical energy measured at the battery terminals per unit battery mass in kilograms, $Wh\text{-}kg^{-1}$) as a function of specific power delivered (watts per kilogram of battery mass or $W\text{-}kg^{-1}$) for three depths of discharge. At a given specific power, more energy can be delivered as the depth of discharge is increased. Full battery depletion occurs when the depth of discharge, d, equals 1.0. A generic battery is

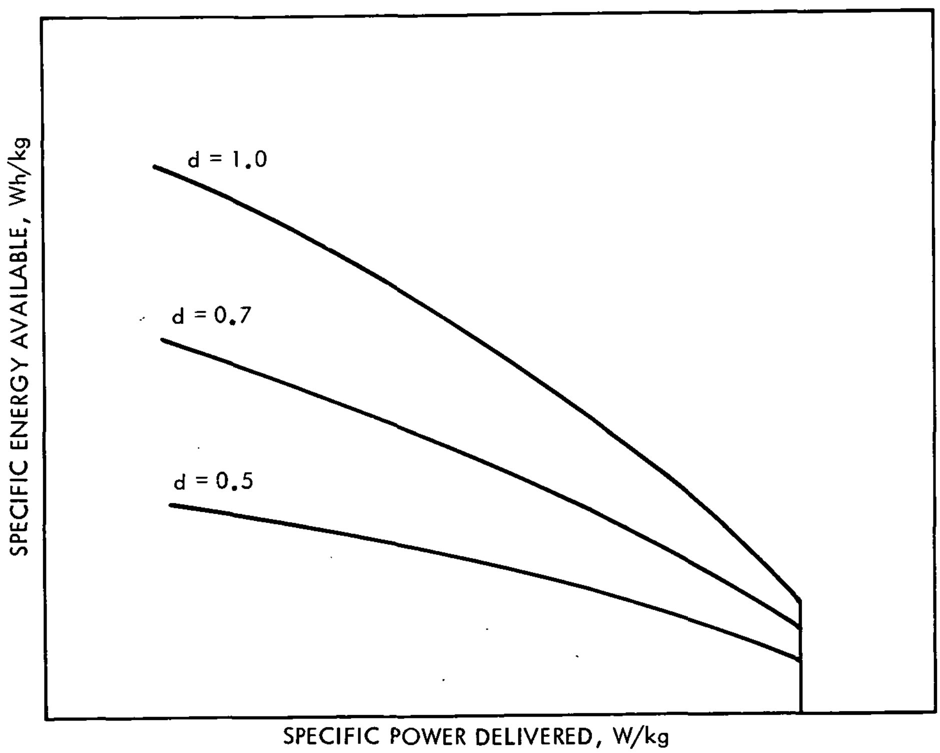


Figure 3-2. Generic Battery Energy Capability

shown. Specific battery characteristics were used in HV simulations and are described in Appendix F.

In order to generate this type of plot, a full-sized traction battery must be discharged into a calibrated load bank at several constant power levels, and measurement made of the energy delivered to the load. Such data do not exist for all batteries being developed for electric vehicles, but estimates of this type of battery performance have been made by JPL for all batteries considered (Reference 4).

As discussed by McDonald (Reference 5), for batteries that fail by electrode degradation, there exists a linear relationship between the logarithm of battery life in cycles and the depth of discharge. The model is repeated discharge-charge cycles to a fixed depth of discharge with battery failure being defined as a percentage loss of capacity. Actual driving cycles will not be as predictable, but the model is nevertheless useful to illustrate the concept of energy throughput (References 5, 6). Lifetime energy throughput, in this model, will be life in cycles times depth of discharge. As McDonald has shown, there is an optimum depth, d*, which maximizes energy throughput. In the discussion which follows, this value and the corresponding battery specific energy vs specific power relationship will be assumed. The sensitivity of this assumption will be examined under Power Systems in Section V.

Figure 3-3 is a typical computer-generated plot of vehicle-specific energy required for various ranges as a function of specific power required to meet acceleration requirements. In order to generate such plots, assumptions

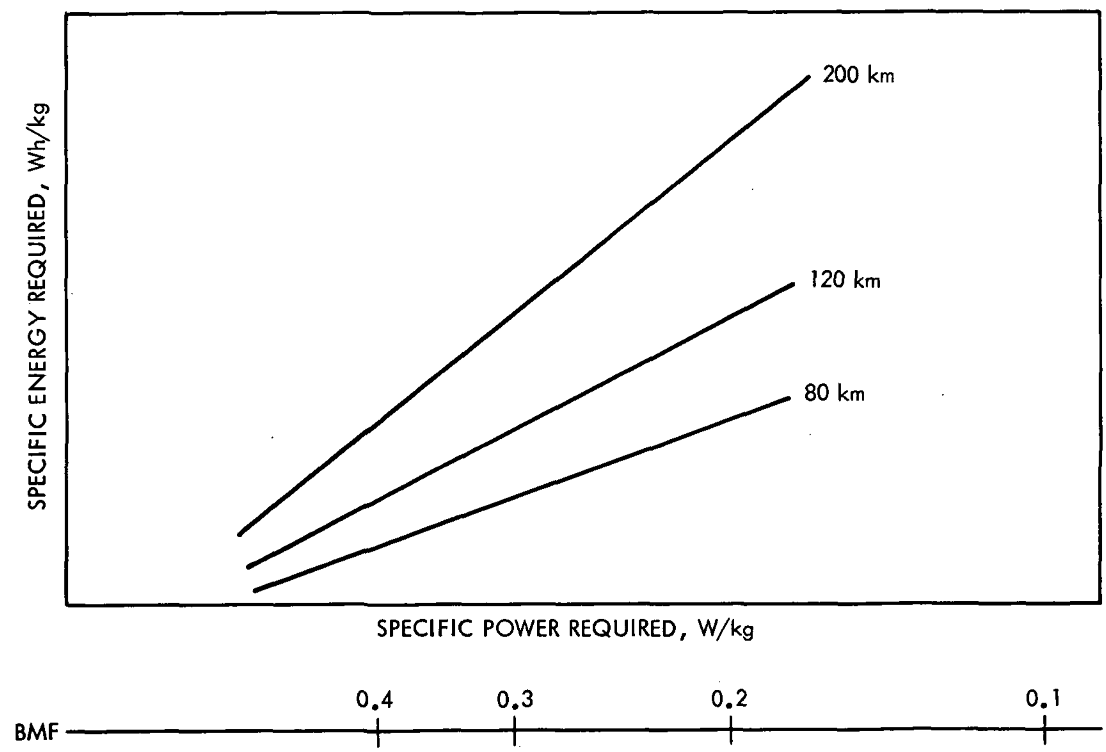


Figure 3-3. Vehicle Energy/Power Requirements

must be made concerning vehicle parameters (aerodynamic drag coefficient, rolling resistance, vehicle mass and mass propagation, subsystem efficiencies, and accessory loads). Assumptions are also necessary regarding required vehicle range and speed-time profiles. A range-dependent combination of EPA Urban and Highway Cycles was used in this analysis. This is explained under Mission Analysis. At this point, Figure 3-3 should also be regarded as generic. More specific results will be presented later. These plots were generated by assuming a traction battery mass fraction, computing vehicle mass, and energy and power requirements, and then dividing by the assumed battery mass. The resulting plots of specific energy vs specific power are shown in the figure.

In Figure 3-3 each line represents a different range requirement, and ranges in km are shown for typical driving cycles. Vehicles are seldom driven at a constant daily range, and realistic annual driving patterns must be constructed from these plots by combining the statistically appropriate set of discrete ranges. This construction is treated in Section V.

In Figure 3-3, it is temporarily assumed that all propulsion power is supplied by the battery. Later in this report a concept of a heat engine which supplements any deficiencies will be introduced. Battery specific power can then be related directly to battery mass fraction (BMF); BMF, therefore, is a parameter which increases from right to left. An auxiliary axis below Figure 3-3 is introduced to show the effect.

The concepts embodied in Figure 3-3 were developed at JPL as a design aid for EV battery subsystems (Reference 2). The approach is not, however, restricted to EVs. These requirement curves are valid for any other type of vehicle and can be interpreted as the requirements placed by the mission and the vehicle on the entire propulsion system, with suitable corrections included for the effects of hybridization. The required ratio between battery specific energy and specific power, as well as the magnitudes of both parameters, are determined by the vehicle and its mission (range and required performance). Battery performance projections of Figure 3-2 can therefore be overlaid[2] on Figure 3-3 to provide estimates of future battery suitability for HV applications (Figure 3-4). In those cases where battery specific energy vs specific power curves fall outside some desired design space (shown shaded), a supplement is required for optimum vehicle/mission suitability. This supplement may be represented as a vector with a specific power component and a specific energy component. This concept guides HV design analysis.

The HV design analysis will be described using plots of vehicle requirements and battery capabilities in specific energy vs specific power coordinates. This is necessary due to the unique power and energy characteristics of batteries. In the conventional propulsion subsystem, energy is supplied by the petrochemical fuel and power is produced by the engine. In the electric traction subsystem, power is provided by the electric

---

[2]This technique was first used by D.V. Ragone (Reference 7).

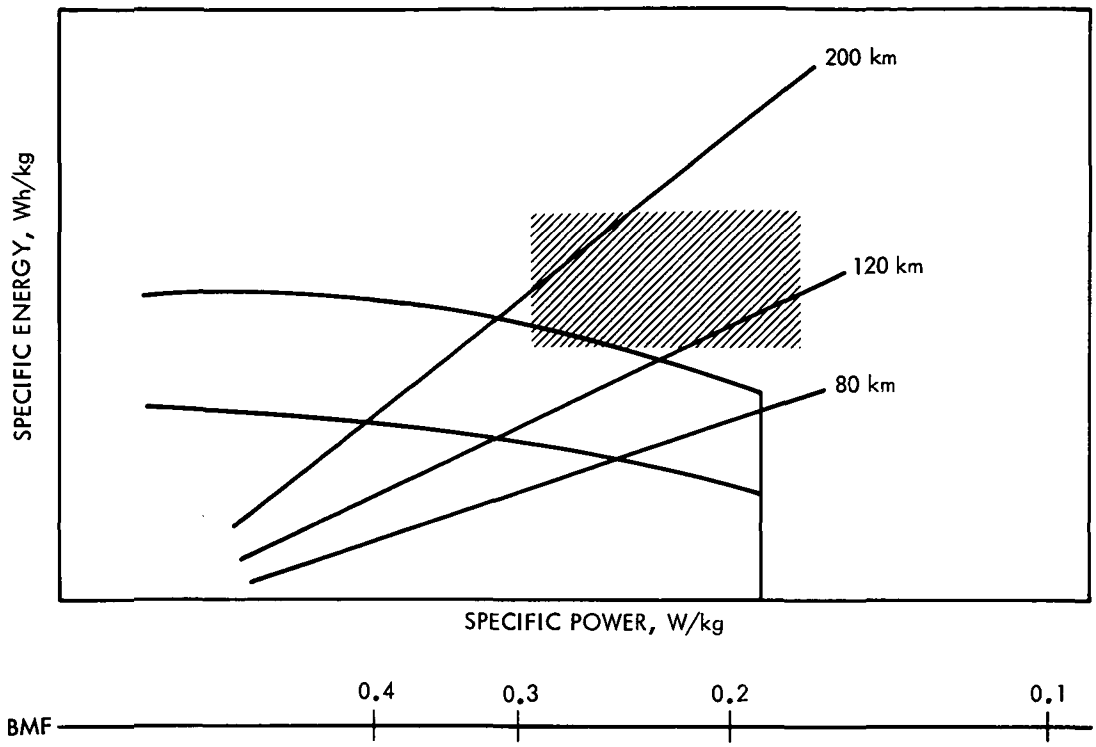


Figure 3-4. Battery Capability/Vehicle Requirements Overlay

motor, but its input function is an interdependent power-energy relationship provided by the battery. Because of this interdependence, simultaneous consideration of both variables is required. In fact, some capability to trade one for the other exists, and one product of HV design analysis is a procedure for making recommendations to traction battery developers for optimum or near-optimum ratios.

It should be understood that there can be no formal battery requirements for HVs in the usually understood sense of the term. Given the goal of petroleum savings, pure electric vehicles provide the greatest savings. Hybrids can serve to introduce electric drive into the national transportation fleet and to limit the drawbacks of near-term traction batteries until full EV operation becomes feasible. If these objectives could be met, the rationale behind HVs would largely disappear. The HV battery requirements, therefore, become EV battery requirements in the limit. During battery development, however, HV battery "requirements" become useful to developers in understanding the specific energy and specific power goals necessary for EV operation, guiding the development of energy and power density, and maintaining the optimum balance between energy and power.

Temporarily restricting the discussion to a single depth of discharge (d_{opt}) and a pair of range (energy) and acceleration (power) requirements will illustrate the conceptual technique of matching battery capabilities to mission and vehicle requirements and of using the heat engine to correct any deficiencies.

Figure 3-5 shows the problem. Given the battery capability (d_{opt}) and two vehicle range requirements (R_1, R_2), assume a battery power level, P. The controller is assumed to limit battery power to this value. (This assumption, though overly simplistic, will illustrate the point. The argument can easily be adapted to power bands rather than fixed values. In actual petroleum consumption simulations, second-by-second computations of required power are made, and the need for this simplifying assumption disappears.) For the longer mission, R_2, assume a vehicle design Point 1. This point determines the battery mass fraction and, therefore, the vehicle weight less heat engine. Because power required at Point 1 is greater than P, the battery will be unable to supply adequate power for full acceleration maneuvers, and a power supplement must be provided by the heat engine. Moreover, because Point 1 is above the d_{opt} curve, the battery will be unable to supply adequate energy to allow the HV to reach range R_2, and the heat engine-fuel system must provide an energy supplement as well to meet this deficiency. Thus, there are both specific power and specific energy deficiencies, i.e., a deficiency vector drawn from the representative battery point (P) to the HV design point (1). For this case, the vector has both a specific power component and a specific energy component. A "peaking" strategy is required to supply the power deficiency, and a "range extension" strategy is required to supply the energy deficiency. For these conditions (low battery mass fraction), the situation is represented by the deficiency vector to Point 1. This situation applies for all Quadrant I deficiency vectors.

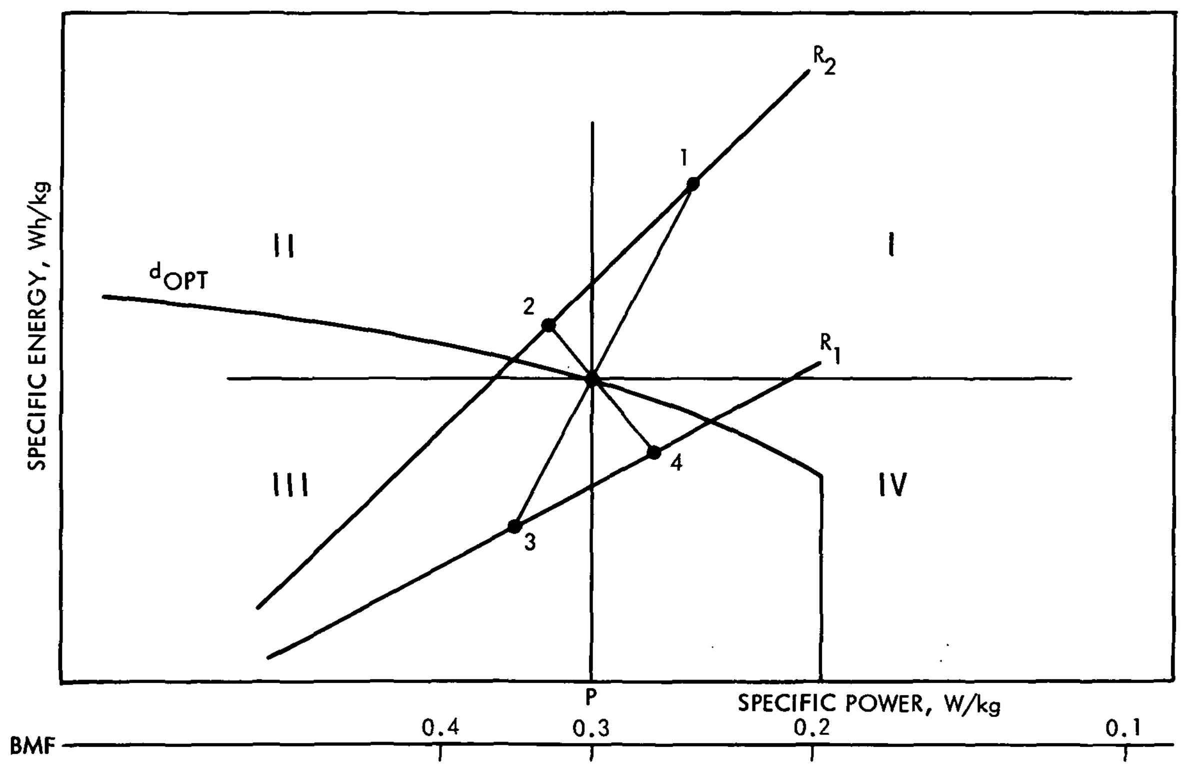


Figure 3-5. Deficiency Vector

In addition, establishing the BMF permits calculation of the mass of the vehicle. The mass model[3], including the hybrid power train, used in this analysis, was

$$M = \frac{M_o + M_h}{1-(1.3 \times BMF)} + 35 + PYLD$$

where

M = vehicle test mass, kg

M_o = vehicle shell mass, kg

BMF = battery mass fraction

M_h = heat engine mass

1.3 = the mass propagation factor

PYLD = SAE payload, 136 kg

The 35 kg represents auxiliary systems whose mass is, to the first order, independent of vehicle mass.

The battery mass fraction, therefore, approaches a maximum value of 1/1.3 = 0.77, corresponding to a vehicle with infinite mass. Practical values of BMF are far less than 0.77. A typical value of 0.40 is usually assumed as the useful upper limit for electric vehicles, somewhat less for hybrids. For a mass propagation factor of 1.3, BMF = 0.4 implies a vehicle approximately twice as massive as a comparable conventional vehicle.

There is no minimum BMF or right-hand boundary in these figures because there is no conceptual minimum battery mass fraction. There is, however, a practical minimum below which the vehicle, depending on its design parameters, can use more petroleum than a corresponding conventional reference vehicle. This effect will be discussed more fully in Section V.

For Quadrant II, the battery has more than adequate specific power (P greater than P_2) but the specific energy remains deficient. In this case, the conventional system is required to supply only the energy necessary to achieve the range and the relatively less demanding "range extension" strategy is all that is required. All deficiency vectors lying in Quadrant II call for this energy management strategy.

Shifting to Quadrant III and requirements line R_1, a somewhat shorter range, illustrates a third situation. Here the battery can supply both power and energy which are more than sufficient. No supplement is required from the

---

[3]More sophisticated mass models are used when evaluating conceptual vehicle designs. The present model is for illustration only.

conventional system and this particular combination of battery, vehicle, and requirements allows unassisted or pure electric vehicle operation. Vectors lying in Quadrant III are characteristic of electric vehicles in general.

Finally, consider a Quadrant IV design point. The battery has insufficient power but adequate energy. The deficiency vector contains only the specific power component and a "peaking" strategy is therefore required.

Thus, the optimum energy management strategy can be considered as a logical result of the relationship between battery capability (power vs energy) and vehicle requirements (acceleration and range). As more complex situations are analyzed, these fundamental relationships will remain valid.

In this discussion, the terms specific power deficiency and specific energy deficiency have been used frequently. The deficiency vector characterizes the mismatch between battery-vehicle and battery-mission. It describes the energy management strategy required, but it does not describe the actual energy and power deficiencies themselves. To obtain power and energy, it is necessary to multiply the deficiency vector components by battery mass. When the appropriate subsystem efficiency corrections are included, rated heat engine power and required fuel tank capacity, respectively, are determined.

As discussed, it is possible to translate from one design situation to another by changing battery mass fraction and/or required range. It is also possible to translate by introducing improved batteries. This has the effect of displacing the battery capability curves upward (improved specific energy) or horizontally to the right (improved specific power). As better batteries are developed, deficiency vectors will become shorter and HVs with lower BMFs and correspondingly lowered mass will become feasible. Both these effects will decrease the petroleum consumption of HVs and bring their operation closer to Quadrant III, pure EV operation.

Having described the basic approach involving quadrants, deficiency vectors, and energy management strategies, there remains the more difficult issue of optimization, i.e., the achievement of maximum petroleum savings, given all the degrees of freedom present in the problem. This is equivalent to asking which deficiency vector is preferred. The minimum deficiency vector does not necessarily mean minimum petroleum consumption. The effect of vehicle mass must be fully considered. Figure 3-6 shows the situation.

F. BATTERY MASS FRACTION OPTIMIZATION

Several design options for the HV are possible, and all are interrelated. First and perhaps most obvious is the variation of petroleum savings with respect to battery mass fraction. This is equivalent to asking which vehicle design point is optimum. The choices are represented by the diagonal arrows along the vehicle requirements line. Low battery mass fractions mean low vehicle mass but impose the most severe requirements on battery specific energy and specific power. Deficiencies can require the conventional system to provide both power and energy. The heat engine duty

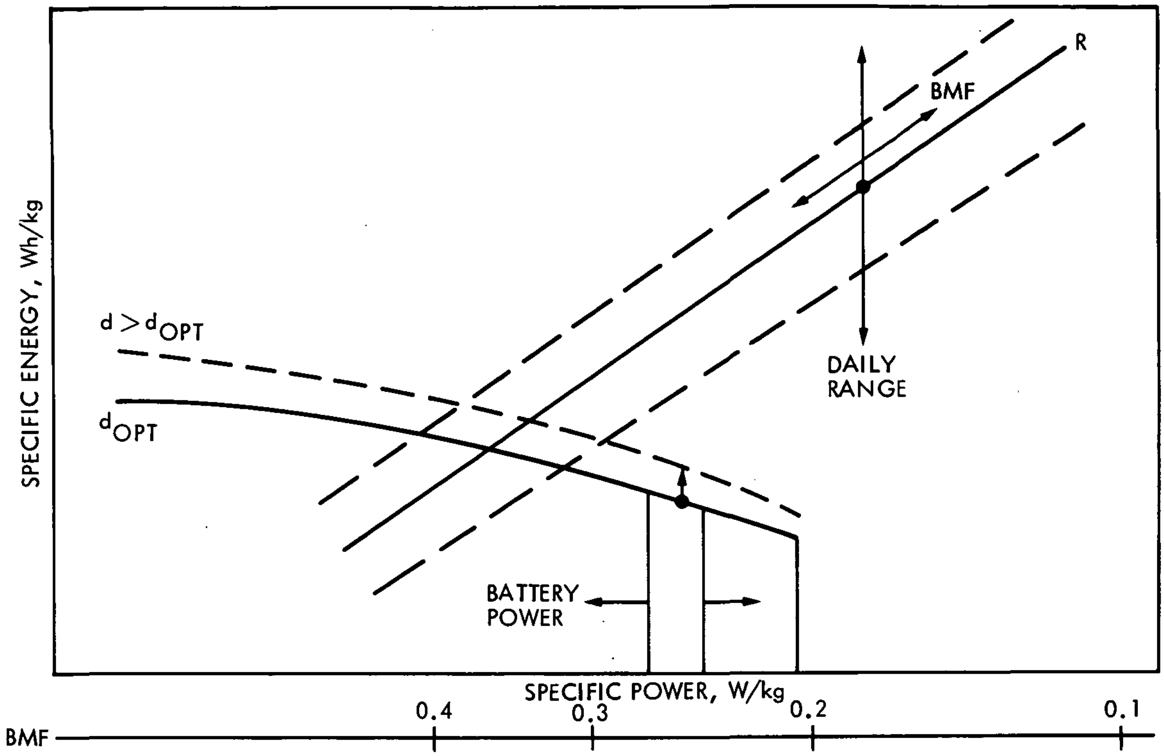


Figure 3-6. Primary Hybrid Vehicle Design Variables

cycle and petroleum consumption are high. As BMF is increased (moving left and down on the requirements line), demands on battery performance are reduced but the vehicle grows larger, heavier, and consumes more energy. Rolling friction, accessories, inertial losses, etc., are increased, and eventually the vehicle becomes too large and too heavy for effective operation. Petroleum savings continue to increase but reach a point of diminishing return. A band of BMFs exists where the battery can supply adequate power and energy and where vehicle mass is reasonable. The optimum is found by allowing BMF to vary and computing petroleum saved over actual driving patterns for each BMF. Specific utility functions are studied to analyze these effects.

G. UTILITY FUNCTIONS

Vehicle value depends on the utility function used to evaluate its petroleum savings. Several choices are possible:

(1) Petroleum saved by the vehicle.

(2) Energy used by the vehicle.

(3) Traction battery mass.

(4) Vehicle mass.

(5) Vehicle cost (first cost or life-cycle cost).

(6) Maintainability and repairability.

(7) Operational safety.

(8) Ratios of these quantities.

As is the usual case in payoff-penalty analysis, ratios were selected because they allow simultaneous consideration of both a payoff function and penalty function, rather than a single payoff function alone.

Ratios should have the form:

Utility function = $\frac{\text{payoff function}}{\text{penalty function}}$ and should be dimensionless if possible.

The actual utility functions chosen for optimization were:

$$\frac{\text{petroleum savings per year (kWh-hr}^{-1}\text{)}}{\text{hybrid vehicle energy expended per year (kWhr-yr}^{-1}\text{)}}$$

$$\frac{\text{petroleum savings per year (kg-yr}^{-1}\text{)}}{\text{hybrid vehicle mass (kg)}}$$

$$\frac{\text{petroleum savings per year (kg-yr}^{-1}\text{)}}{\text{reference vehicle petroleum used per year (kg-yr}^{-1}\text{)}}$$

These are denoted respectively as PS/TE (petroleum savings per unit total source energy), PS/M (petroleum savings per unit HV mass), and PS/RVF (petroleum savings per unit reference vehicle fuel).

These quantities were chosen for optimization because they are ratios of the primary payoff function (petroleum saved) to vehicle system penalty functions (vehicle mass and total annual energy used). Although petroleum saving was the clear choice for the payoff function, several choices were available for the penalty function. Examples are vehicle-first cost, vehicle-life cost, break-even gas price, and battery mass (rather than vehicle mass and total annual energy used).

Credible cost figures, estimates of maintainability/repairability, and safety assessments require actual vehicle designs and mass-production cost estimates. The analyses completed in this study were not sufficiently detailed to allow development of actual HV designs (a subject best left to the OEMs). Follow-on HV studies will consider cost factors. Penalty functions involving cost, maintenance, repair, and safety were deferred, although they might be preferred in future HV design work by the industry.

Battery mass is an adequate penalty function; however it is only part of total vehicle mass. Vehicle test mass grows more rapidly than battery mass

$$M = \frac{M_o + M_h}{1 - (1.3 \times BMF)} + 35 + PYLD$$

and the vehicle as a system is penalized by total mass, not battery mass alone.

Similar arguments can be made against other available penalty functions. Several penalty function choices are available and other payoff functions as well. These may depend on the particular application at hand (conceptual design, feasibility study, engineering development, or production design, etc). The intent of this analysis has been to develop a general method tailored to the particular requirements of the DOE and that approach was pursued from the beginning. Vehicle mass and energy expended were selected as the most appropriate penalty functions and petroleum savings optimizations were developed on that basis. Both utility functions are presented with petroleum savings per unit total source energy preferred as the most illuminating function, making the third utility function. Petroleum savings per unit reference vehicle fuel used are also included as a dimensionless utility function.

There are two energy-related issues in HV development. One is the conservation of petroleum and petrochemically derived energy. The other is the conservation of total energy, whether derived from petroleum or not. Total annual energy used by the HV is one primary penalty function. The ratio of the two is taken as the primary utility function for this study. It should be high for the most useful vehicles.

H. DESIGN OPTIMIZATION

Proper battery management requires that the battery be matched to the vehicle and that the vehicle be matched to the mission. If the vehicle's daily range exceeds its electric range capability, the heat engine becomes the prime mover and petroleum displacement no longer occurs. A petroleum penalty is, in fact, incurred by increased heat engine operation. The petroleum saved by HVs is, therefore, a strong function of distance driven beyond the vehicle's electric range. Because only 5% of the HV's battery energy will be petroleum-produced in 1990, the daily distance driven on batteries does not strongly influence the petroleum displacement. Beyond the vehicle's electric range, however, all required vehicle energy is produced by petroleum. The annual petroleum displacement, therefore, can depend strongly on the daily driving cycle and proper energy management. The quantity of interest is

$$\text{fuel used (kg)} \doteq \sum \frac{\text{(driven range - electric range)}}{\text{kilometers per kg of fuel}}$$

$$+ 0.05 \times \frac{\text{kg}}{\text{kWhr}} \times \sum \text{driven range} \times \frac{\text{kWr}}{\text{km}}$$

The first sum represents fuel burned by the HV and is taken over those days when the driven range exceeds the electric range. The second sum represents fuel required for electric power production and is taken over those days where the HV electric range exceeds the driven range, one battery recharge per day being assumed. The kg/kWh factor is the efficiency of conversion and transmission of petroleum energy to electrical energy and the factor 0.05 is the predicted 1990 fraction of electric power produced from petroleum in the United States. Battery recharge through regeneration can be included as a correction to both sums if the vehicle design allows.

Because HVs are heavier than conventional vehicles, they can have relatively higher total energy consumption. When this energy is 100% petroleum-produced, a penalty may be incurred by the HV. This suggests two things. First, it is an inappropriate use of an HV to force it to perform consistently beyond its electric range. Doing so will produce relatively poor HV fuel economy. Second, it is an inappropriate use of an HV to force it to perform consistently well short of its electric range. In this case the primary reason for vehicle hybridization, the avoidance of the range limitation, has disappeared and an EV would be more suitable. The best HV use pattern for petroleum savings is to operate the vehicle at or as near its electric range as often as possible, using the heat engine to provide required performance and some range extension when required. This logic will later be reversed to assist the HV designer who seeks the most appropriate electric range for maximum petroleum savings, given the driving statistics. This is equivalent to asking which battery mass fraction is optimum.

Figure 3-6 shows another degree of freedom present at the vehicle design point. This is the arrow representing the effect of varying the vehicle's daily range. Here the battery mass fraction is considered fixed, and actual driving conditions are varied, above and below the range requirements line R. Although this effect is beyond control of the HV designer (daily driving cycles and annual driving patterns are determined by the consumer), it must be analyzed for its effect on petroleum savings. The question is whether high BMF vehicles are more severely penalized when driven short distances than low BMF vehicles when driven long distances. This must be answered by considering actual trip distance and frequency statistics. In the HVA this was done by constructing realistic annual travel patterns from actual data for the missions considered. These patterns are described under Mission Analysis. Results of vehicle simulation are presented in Section V.

The requirements line itself can also change, reflecting a variation in power requirements (shift along the horizontal axis) and a variation in energy requirements (shift along the vertical axis). A horizontal shift can result from a reduction in required vehicle acceleration, a vertical shift from improvements in drag-area product, rolling resistance, or inertial losses. The situation is shown in Figure 3-6 by dotted lines.

Having described the four degrees of freedom surrounding the vehicle design point, there remain three degrees of freedom about the battery capability point which must be discussed. This is represented by the set of lower arrows in Figure 3-6.

The vertical arrow represents the use of battery energy. The existence of a "best" depth of discharge for the battery has been described. It maximizes the lifetime energy throughput of the battery. The issue in this study is not, however, the optimization of lifetime energy throughput. It is the optimization of petroleum savings. (Cost optimization will require consideration of lifetime energy throughout.) Recognizing that vehicle petroleum saving is penalized by any vehicle mass, particularly a mass associated with unextracted battery energy, the question becomes whether deeper-than-optimum battery discharges increase or decrease petroleum savings. Clearly, depths of discharge below the optimum, d_{opt}, are undesirable. The tradeoff arrow is shown in one direction only.

There is also the issue of the best allowable power band for battery operation. Higher allowable power usually decreases specific energy available from the battery but means a reduced duty cycle for the heat engine in engine peaking strategies. Reducing the allowable maximum battery power means altered electrical traction subsystem efficiencies and more energy available but results in more frequent and longer duration engine operation. Optimums exist which maximize the utility functions. They are clearly battery-specific (dependent on the slope of the battery capabilities curve) as well as energy management strategy-specific and must be found by iteration.

Finally, there is the issue of battery performance improvement. Improved specific power will improve petroleum savings, but the effect must be quantified before it can be ranked in importance. All effects can then be compared and the most promising payoffs identified as areas recommended for continued development.

To summarize the optimization procedure, six primary effects have been investigated. They are the variation of the utility functions with:

(1) Battery mass fraction.

(2) Driving patterns.

(3) Acceleration and gradeability requirements.

(4) Vehicle energy loss parameters.

(5) Battery specific energy and depth of discharge.

(6) Battery power required.

These effects are illustrated conceptually in Figure 3-7. Specific results appear under HV Power Systems in Section V.

Other effects have also been investigated. They are variations of the utility functions with:

(1) Vehicle configuration (series vs parallel).

(2) Type of heat engine (Otto vs diesel).

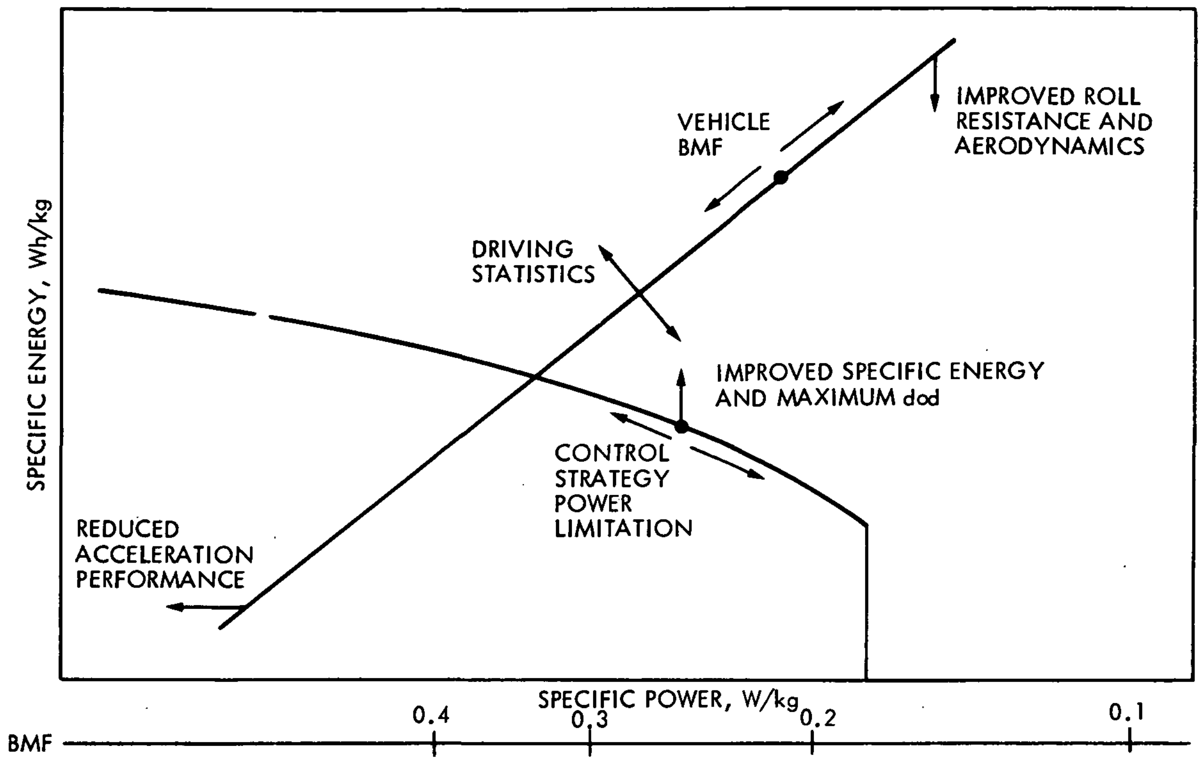


Figure 3-7. Conceptual Hybrid Vehicle Design Optimization

(3) Regeneration (with vs without).

(4) Vehicle mission.

(5) Battery type.

(6) Accessory loads.

(7) Engine peak power.

(8) Gear ratios, differential ratio.

(9) Transmission efficiencies.

(10) Engine on/off operation.

These results are also presented under Power Systems in Section V.

The preceding description of analyses in the general HV design space is actually a sensitivity analysis. Although sensitivity analyses are, in fact, accomplished by computer simulation, the procedure has been described in specific power, specific energy coordinates with associated deficiency vectors to assist in understanding the trade-offs with a graphical picture. When sensitivity analysis results are presented, this graphical method will give a picture of the process.

The basic procedure for HV design optimization has been described. It is the result of the systematic analysis of HV design parameters (principally the battery capabilities and BMF) and HV characteristics. The results are optimum BMF and best energy management strategy for the vehicle. They are logical consequences of the deficiency vector, and they determine the petroleum consumed in meeting the performance and range requirements of the vehicle. The HV design point, vehicle characteristics, driving patterns, battery use, and electrical control strategy all exert effects on the utility functions, and analysis of all factors is necessary for proper optimization.

I. BATTERY CHARACTERISTICS

The first effect, that of the varying energy availability as a function of power demanded, was discussed previously (see Figure 3-2). The second effect, the ability of the battery to deliver power with decreasing state of charge also has important implications for HVs.

For most of the batteries considered, as discharge proceeds, specific power is decreased. This battery characteristic is most easily seen on a plot of power available vs energy delivered (or depth of discharge) and is frequently referred to as battery "stiffness". Heat engine vehicles, of course, exhibit no such characteristic, and this principle and its implications are absolutely fundamental to the operation and performance of HVs. Recent JPL experience with Ni-Fe electric vehicle batteries, for example, has shown that stiffness may be controllable within limits by the battery manufacturer. Ni-Fe and Ni-Zn batteries appeared to have improved stiffness in the JPL Upgraded Demonstration Vehicle Test Program (Reference 8). Electrode fabrication techniques, electrode geometry, and separator characteristics all affect battery internal resistance and therefore affect power available as a function of battery SOC.

Evidence also exists to suggest a trade-off between battery stiffness and the cycle life for most battery couples. As battery stiffness plays a fundamental role in the performance of traction batteries, it must be given thorough analysis by battery manufacturers. Maximum electric power deliverable to the drive system is a function of battery DoD. Although selection of an inherently stiff battery can minimize these effects, proper interpretation of SOC indications is essential. It is precisely the hybrid nature of the power plant, however, which offers an alternative to this feature of electric traction systems. With proper energy management, the effects of battery stiffness on propulsion performance can be minimized because, under conditions of power deficiency, the heat engine can be commanded on. Proper design of the HV energy management system can make the vehicle independent of the battery DoD. Independence was, in fact, assumed to be a requirement for safe HV operation in this study.

There is another parameter which is also important in power control circuits, the control subsystem threshold voltage. Below this voltage, the controller is unable to accept sufficient power to meet required vehicle performance, even though there may still be adequate power available from the battery. The battery must therefore be sized to ensure not only an adequate power capacity, but the controller must be designed to provide adequate power

at the motor terminals as the battery is discharged. The battery and motor/controller form an integral subsystem with combined characteristics that determine the vehicle performance characteristics in electric drive (and the duty cycle of the heat engine). Finally, battery self-heating depends on the usual I^2R relationship. As heating of traction battery systems may play an important role in affecting the power available for delivery, the effects of resistive self-heating during charge and discharge must be considered in battery thermal management.

These effects are mentioned here because of their importance to production HVs. They are sensitive to both controller design and battery type. They were not given detailed consideration in this analysis.

J. VOLUME CONSIDERATIONS

Just as there is an optimum specific power-to-specific-energy ratio, there is also an optimum power density-to-energy-density ratio. The governing parameter is no longer vehicle mass but rather vehicle volume. If either ratio is non-optimum, the electrical system will be correspondingly deficient, and the heat engine-fuel system must supply the deficiency.

Packaging and placement of subsystems within HVs is an important issue as well. Vehicle configuration (series vs parallel) can be influential in determining front-to-rear axle weight distribution and therefore HV handling qualities. Subsystem placement can also affect vehicle maintainability through accessibility for maintenance and repair. Although heavier, the series configuration is inherently more flexible than the parallel. In series configurations the two traction subsystems can be independently located.

K. MISCELLANEOUS ISSUES

The sensitivity of HVs to weight is well known and is borne out in modeling and simulation studies. In fact, weight reduction is the most effective method for reducing energy consumption in any vehicle. The use of lightweight materials in HV development will continue to be important. General Motors Research Labs has expressed the importance of weight reduction in the following way in referring to a pure electric two-passenger vehicle.

> "The body will be made of premium lightweight materials to minimize weight because each additional pound of weight in an EV has as much effect on driving range and performance as 3 lbs in a car powered by one of today's internal combustion engines." (Reference 1)

The 3:1 effect mentioned will be smaller for the HV and will, of course, depend on configuration and energy management strategy, but mass reduction is still the most effective way to reduce fuel consumption. Unless breakthroughs are made in battery technology, the specific power and specific energy of the traction batteries will remain below that of conventional systems. For HV performance equal to that of a conventional car, the HV power train must, therefore, be larger and heavier. A heavier chassis, suspension, etc., will also be required.

The sensitivity of HVs to the product of aerodynamic drag coefficient and frontal area (the drag-area product) must also be considered. As vehicle weight is reduced, this product becomes increasingly important, particularly at cruise speeds where aerodynamic loads predominate. The most important HV parameters in reducing aerodynamic loading are battery power density and battery energy density. These battery performance parameters exert first-order effects on required battery volume, to some degree on vehicle frontal area, and on battery packaging considerations. The use of flush-mounted windows, underbody fairing, exterior size reduction, and rear-end optimization (boat-tail/fairing for the best combination of flow-separation drag and vortex-generation drag, respectively) will benefit HVs and will therefore be an important factor in extending the highway electric range of vehicles which are energy limited. These considerations are not, of course, limited to HVs, but they exert important effects on electric range and petroleum consumption.

Critical subsystem packaging limitation and packaging densities greater than conventional cars characterize HVs. This makes maintenance and trouble-shooting more difficult in HVs because of limited volume and accessibility restrictions. Detachable fairings, quick access panels, and other techniques for easy accessibility may also be required for production vehicles if cost control of maintenance and repair are important.

Although not a prime subject for developmental vehicles, the crashworthiness of HVs will be an important feature of production cars. Packaging considerations during development may dictate some non-optimum arrangements for certain components or subsystems to allow adjustment, maintenance, troubleshooting, etc. The presence of high current, high voltage electrical systems, possibly elevated temperature batteries, and relatively large quantities of toxic battery materials will require that special attention be devoted to the issue of crashworthy packaging in production cars. Electrical guillotine devices actuated by two-axis or three-axis g-sensors may be required to meet standards for bumper impact, side impact, rollover, etc.

Analysis of the probable driving cycles indicates that, although rapid battery recharge (typically 10-30 min) might eventually be desirable, the feature is not now required, at least for HVs. A 6- to 8-h recharge time each night appears to be adequate for present and near-term usage patterns. In fact, rapid recharge would require high current recharge stations, typically 100 A or greater with inherently higher battery thermodynamic losses. Such high current facilities do not exist in ordinary home service and, even if they were installed, they would increase, rather than decrease, the load management and petroleum supply problems of electric utilities. Special utility as well as consumer facilities would be required for such high current recharge, and the lowered recharge efficiency plus the relatively unknown, but suspected, effects on battery life make rapid recharge an option with dubious value.

Vehicle hybridization also offers promise for pollution abatement. Emissions from coal-burning power plants can be controlled. Emissions from nuclear plants are effectively nonexistent. Pollution control from individual auto engines has proved to be a formidable technical challenge with its own

set of problems and costs. On a per-kWh basis, emission control seems most effective when electric power is centrally produced, distributed, and converted rather than produced by individual and relatively small vehicle-mounted engines. These benefits will be greatest when the HV operates within its electric range. As energy production is shifted to the heat engine, the pollution naturally reappears, although tuning of the heat engine and/or fixed point operations can reduce this effect.

A characteristic of HVs is the need for a passenger compartment heater independent of the heat engine. As heat engine operation may be intermittent or even be unused on trips within the electric range, its rejected heat is not always available for use. Electric motor cooling is by natural convection and is therefore not suitable for passenger compartment heating. An independent heater may hence be required. An air conditioning system can be mechanically or electrically driven and need not be specially developed for HV use, although a split-cycle heat pump could offer some weight-saving advantages over separate heating and air conditioning systems. Thermal conditioning of the traction battery may also be required, and this function should be integrated, if possible, with passenger space conditioning. Analysis at JPL has resulted in a preference for a split absorption heat pump/refrigerator for the HV (Reference 9).

A caution and warning system specifically designed for HVs will be required. Traction battery temperature indicators and motor over-temperature sensors will be required. If the benefits of a fail-safe, fail-soft control system are to be realized, some instrument panel readouts and control system overrides will be required along with health monitors for the energy management and control system. The overall effect will be an increase in the complexity of the caution and warning system for HVs over those in conventional vehicles.

The generation of high-frequency electromagnetic interference is a characteristic of dc as well as ac drives. In dc power systems, current choppers generate high frequencies, pulse leading, and trailing edge frequency components, in addition to the basic pulse frequency. In ac systems, inverters generate harmonics of the system base frequency as well as pulse leading and trailing edge components. Proper vehicle design must consider these effects and take appropriate precautions by shielding and filtering to preclude interference with or power transfer to other vehicle circuitry.

Regardless of the HV configuration (series or parallel) and electric power form (ac or dc), the electric motor, the heat engine, and the power blending features of the vehicle controller must be individually testable during troubleshooting and routine maintenance. This will mandate some fairly sophisticated vehicle maintenance procedures and may require the test conductor to be able to override the normal control system logic of the vehicle. Necessary features will include provision for on-line diagnosis, troubleshooting, and limited monitoring of selected HV subsystem operation.

SECTION IV

MISSION ANALYSIS

A. INTRODUCTION

This chapter describes the vehicle missions analyzed in the Hybrid Vehicle Assessment. Mission analysis is the logical starting point for the HVA, because the development of HV functional requirements must come from expected vehicle usage patterns. Mission analysis allows the identification of promising automobile missions by understanding and modeling trip purpose, payload, travel patterns (annual use), and driving cycles (daily use). Such characterization allows the comparison of different automotive technologies which are equivalent in function and minimum performance capabilities. The results of HV mission analysis are transferred directly to HV power systems analysis for computer modeling and simulation.

The petroleum savings offered by HVs are strongly dependent on expected daily driving cycles. It is important, therefore, to understand how HVs would be used and to develop driving cycles to evaluate them so that appropriate, as well as inappropriate, missions can be identified.

The primary objective of mission analysis was to identify vehicle missions for the 1990s in order to predict those mission-related characteristics necessary in an HV designed as a prototype for introduction into the U.S. transportation fleet.

The travel data used in this analysis were taken from the 1978 Nationwide Personal Transportation Study (NPTS) (Reference 10). A basic assumption in developing automobile missions was that travel pattern trends revealed by the NPTS will continue in the near future. This assumption was severely tested during the 1973 oil embargo when both petroleum supply and price were disrupted. A major shift has occurred since then toward preferences for smaller automobiles. This shift has allowed consumers to maintain a roughly constant degree of mobility without the full impact of increased gasoline bills. Although some changes have also been observed in the size of daily driving distances and annual patterns, the basic patterns have remained essentially intact.

The Nationwide Personal Transportation Study (NPTS) was updated from 1977 to 1978 (Reference 10). This NPTS provides a new data base reflecting changes in automobile travel and recent trends in transportation patterns. The HVA is based primarily on the most recent NPTS data and the trends which have developed since 1969 (Reference 11).

The purpose in making projections of automobile travel patterns for 1990 was to predict the most important features of expected vehicle missions during the period. In making these automobile travel projections, it was assumed that the level of mobility then will be similar to that experienced today. In addition, most of the extrapolations of travel patterns are based on the trends reflected by the two surveys.

In characterizing vehicle missions, it was assumed that annual driving patterns could be constructed from daily driving cycles having the same statistical properties as those in the NPTS data. Specifically, HVA vehicular missions were characterized by:

(1) Trip purpose.

(2) Payload (vehicle occupancy and cargo).

(3) Annual travel pattern.

(4) Daily travel distance.

(5) Minimum performance requirements (speed, acceleration, and gradeability).

Five missions were chosen. They are discussed in detail in this section.

Table 4-1 shows how vehicle ownership has changed between 1969 and 1978 and gives projections for 1990. A major change has occurred between 1969 and 1978 in the proportion of households owning two or more automobiles, and this trend is expected to continue. Forty-three percent (33% + 10%) of the households are projected to own two or more vehicles by 1990.

This change has an important implication for HV acceptability. Hybrid vehicles are slightly less versatile than conventional vehicles. Multiple auto ownership, however, offers a household more flexibility in matching a vehicle to a mission, and HVs may therefore be more acceptable in multiple-car households. Because the number of autos per household is increasing, the market for HVs in a petroleum scarce environment can be assumed to increase as well.

Figures 4-1 and 4-2 show trends and projections for the 1990s (Reference 12). Figure 4-1 shows distribution of new car sales by vehicle size. Figure 4-2 shows total fleet population projections. The trends indicate that consumers have been showing increased preference for downsized

Table 4-1. Household Automobile Ownership

Number of Autos Per Household	Percent of Households NPTS 1969	NPTS 1978	Projection 1990
0	21.1	17.9	15
1	47.4	45.2	42
2	27	28.7	33
3 or more	4.5	7.2	10

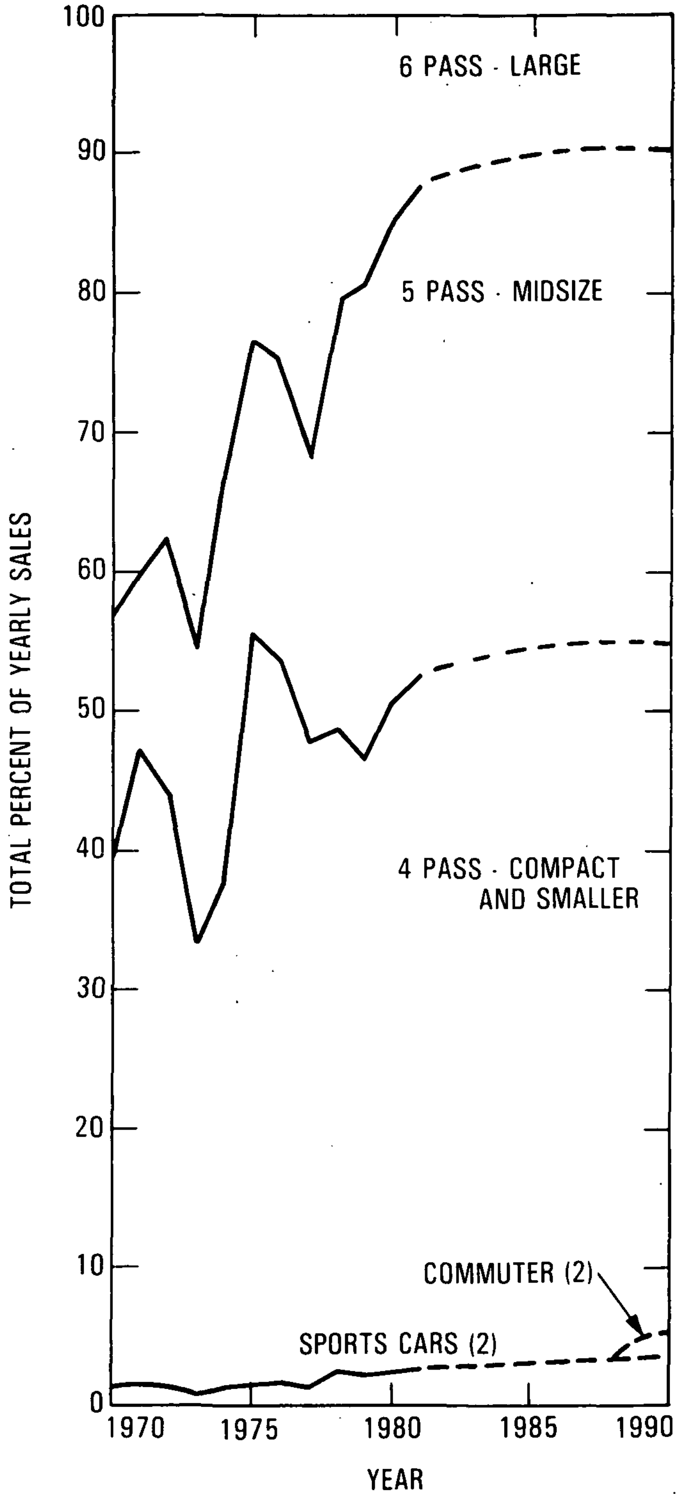


Figure 4-1. Distribution of New Car Sales

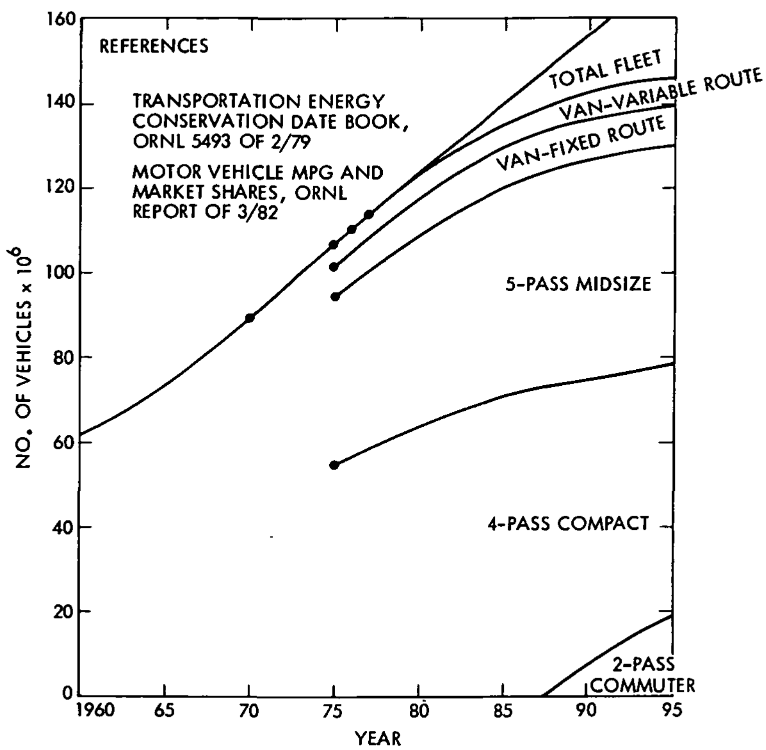


Figure 4-2. Trends in U.S. Auto Fleet Mix

automobiles. The primary cause of the shift to smaller fuel-efficient automobiles has been the rise in price of gasoline over the past decade. Compact and subcompact automobiles are projected to account for 51% of the fleet in 1990. A small market for the two-passenger commuter vehicle is assumed to occur starting in 1988. The biggest reductions are projected in the proportion of four-passenger and six-passenger automobiles. Major changes in fleet mix are considered unlikely beyond 1985 unless significant changes take place in gasoline supply and demand.

B. VEHICLE MISSIONS

For this study it was necessary to describe as much of U.S. travel in as few separate missions as possible. The criteria used in selecting vehicle missions were as follows:

(1) Missions should account for a major portion of transporation fuel consumption.

(2) A wide variety of vehicle types should be included, representing both current and some hypothetical vehicles.

(3) Missions should represent a wide variety of travel patterns and driving conditions.

The five missions selected are summarized in Table 4-2.

Table 4-2. Vehicle Missions, Functions, and Payloads

	Mission I General-Purpose Vehicle	Mission II General-Purpose Vehicle	Mission III General-Purpose Vehicle	Mission IV Fixed-Route Delivery Van/Truck	Mission V Variable-Route Delivery Van/Truck
Primary Function	Commuter travel	Family travel	Family travel	Commercial use	Commercial use
Secondary Function	Family business and other travel				
Maximum Payload	Two passengers, 50 kg	Four passengers, 100 kg	Five passengers, 150 kg	Two passengers, 500 kg	Two passengers, 700 kg

These missions are based on specific vehicle size and weight characteristics as well as the volume available for power train subsystems. Potential petroleum saving was a primary consideration in assessing the conceptual HV design features which each would require.

Figure 4-3 shows total estimated annual fleet distance by mission for 1977 and 1990. The estimates were made by multiplying fleet sizes for both years by the 50th, 75th and 90th percentile distances for each mission. Bar heights represent total U.S. fleet distance up to and including the respective percentile. Distance data for the van missions are less detailed. Only one fleet mileage estimate is made, that for the assumed 50th percentile.

Analysis of NPTS data indicates that 75% of all vehicles are used in some way for work-related travel. The occupancy figures for work-trip travel show that 85% of vehicles have only the driver and 93% of work trips have less than three occupants. A two-passenger commuter vehicle could be attractive as an HV if the public could be persuaded to match vehicle to mission. Considering the small number of vehicles involved and the low fleet mileage projections, however, this mission was not considered as a likely target for petroleum savings. Conceptual HV designs were developed, but they were carried forward only until the major design features were well understood.

The NPTS data also indicate that the flexibility of petroleum-powered vehicles allows them to be used for a variety of purposes, except for any limitations imposed by size or payload, generally describable as family travel. Two missions were selected with this primary purpose. They are differentiated only by payload capacity, Mission II being a four-passenger and Mission III being a five-passenger vehicle, with slightly higher payload. These two vehicle sizes were selected to reflect differences in consumer preference. Projections of U.S. fleet composition indicate that midsize and

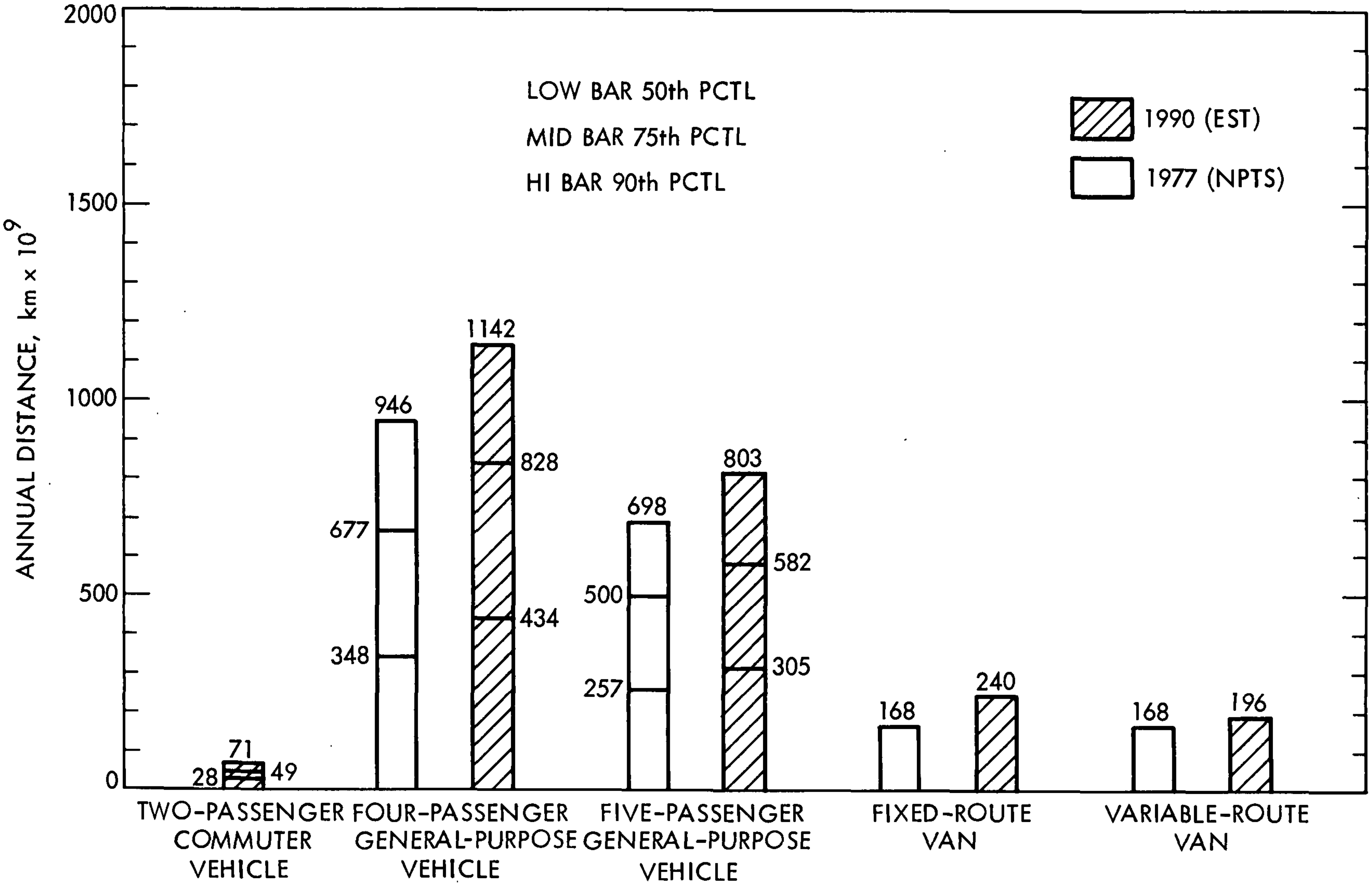


Figure 4-3. Estimated Total U.S. Annual Fleet Distance by Mission

smaller vehicles will account for over 85% (89% minus 4%) of the vehicle fleet in the 1990s. For these missions, 95% of all trips had four passengers or less and almost 98% of their trips had five occupants or less. The large number of fleet miles driven on these missions (see Figure 4-3) makes the vehicles prime targets for HV applications.

The growing popularity of small trucks and vans has resulted in their use for a variety of missions. The NPTS data indicated that the combination of vanbus/minibus, van and pickup trucks represented over 15% of the 1978 U.S. automotive fleet. Thus van/truck missions represent not only a substantial proportion of the fleet, but also account for sizeable fuel consumption. Two missions were chosen to represent the van/truck missions, the fixed-route delivery and the variable-route delivery truck/van. These vehicles allow substantial design packaging flexibility compared to automobiles, and conceptual HV designs were developed primarily for that reason.

Other transportation functions identified included the all-purpose six passenger vehicle, the taxi, and the vacation rental vehicle. The six-passenger all-purpose vehicle was dropped from consideration because it represents a small segment (11%) of the projected fleet in late 1980s. The taxi fleet represents less than 1% of the total U.S. fleet, according to the recent NPTS data. Taxis, in general, are high-mileage vehicles; the average annual travel is over 50,000 miles. The taxi use pattern varies considerably, depending upon whether the vehicle is used in a dense metropolitan area or in a rural area. Taxis were deleted from consideration as a vehicle mission primarily because they represent a small segment of the vehicle fleet and because of their unattractive daily cycle. The vacation rental vehicle was deleted from consideration as a mission because of its use pattern, heavy daily travel for a few days per year, an undesirable pattern for any hybrid vehicle.

C. ANNUAL TRAVEL PATTERNS

The NPTS data describe the travel of a sample of U.S. families on a single day. The JPL analysis extrapolated those daily data into annual pattterns. A basic assumption made in developing annual travel patterns is that total annual travel can be represented by the accumulation of NPTS-like daily trips. It was assumed that the trip length frequency distributions contained in the NPTS data were statistically valid representations of trip lengths encountered by a typical household. The number of daily trips, a random variable with integer values, was approximated by a Poisson distribution.

The average trip length based on the 1977 to 1978 NPTS data was 13.2 km, and this average was assumed in this study as well. Thus, a vehicle making 1,000 trips annually will be driven approximately 13,200 km (13.2 x 1000), resulting in a mean of 1,000/365 to arrive at 2.73 trips per day. Using 2.73 as the mean number of trips per day, the probability of making "x" trips on any day was estimated from the Poisson distribution

$$P(x) = \frac{e^{-u} u^{x}}{x} \qquad (u = 2.73)$$

where "x" is an integer with values from 0 to 12, the assumed upper limit of the number of trips made on any day.[4]

For each of the 365 days in a year, a Poisson-distributed random integer was drawn to represent the number of trips expected on that day. Each trip length was then drawn randomly from a trip-length distribution constructed from the NPTS data. By accumulating daily travel in this manner, annual travel patterns were constructed with the statistical properties of the NPTS data. A typical annual pattern for Missions II and III appears in Appendix B. Such patterns were used to evaluate the annual petroleum savings of HV conceptual designs. That evaluation was made by HYVEC IV simulation. and is described in Section V.

1. Mission I - Commuter and Family Business

The primary purpose of this mission is commuter travel. However, some use for other trip purposes was also assumed, such as personal business and social or recreational trips for which a two-seat vehicle was sufficient. The one-way work trip distance was projected to be 10 km, 18 km, and 36 km for 50th percentile, 75th percentile, and 90th percentile vehicles, respectively. The annual mileage for these vehicles was estimated from the work trip distance plus other travel and assumed to be 3,000 km/yr. In all cases work trips were assumed for 250 days of the year, resulting in the annual travel as shown in Table 4-3. Figures 4-4 and 4-5 show the distributions of work trip distance based on the NPTS data. Figure 4-4 shows the percent of days vs distance. Figure 4-5 shows the expected annual vehicle kilometers traveled (AVKT) vs distance for 75th percentile vehicles.

Table 4-3. Annual Travel for the Two-Passenger Commuter Vehicle Mission

Annual Distance Percentile, %	Work Distance, km	Annual Work Travel, km	Other Annual Travel, km	Total Annual Travel, km
50	10	5,000	3,000	8,000
75	18	9,000	3,000	12,000
90	36	18,000	3,000	21,000

[4]This procedure was developed by Schwartz (Reference 13) to estimate electric vehicle range requirements and later used by Surber and Deshpande (Reference 14) in an assessment of hybrid vehicles. It effectively constructs one typical vehicle's annual driving pattern from a collection of daily distance data for many vehicles. This procedure is required because no data are available describing how individual vehicles are used. This topic is well treated in Reference 14.

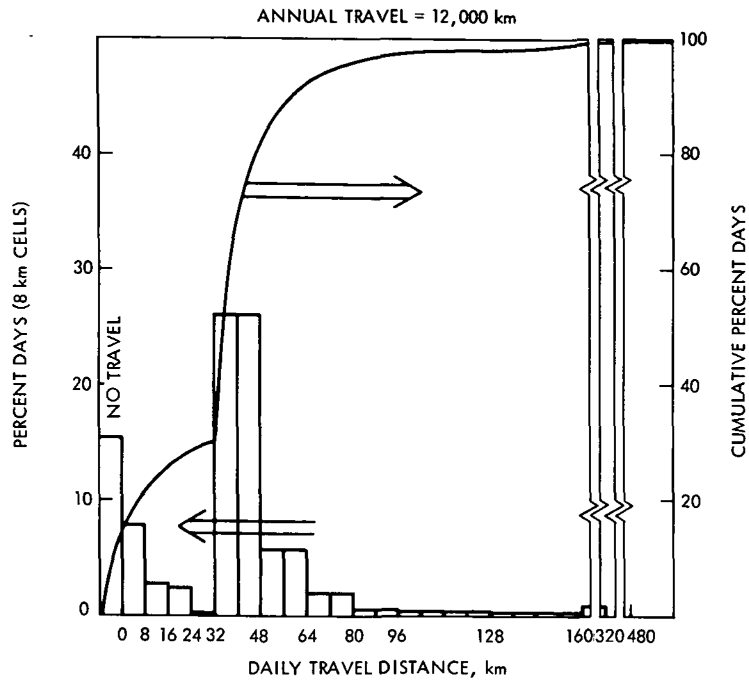


Figure 4-4. Annual Travel Pattern Mission I, Commuter Vehicle

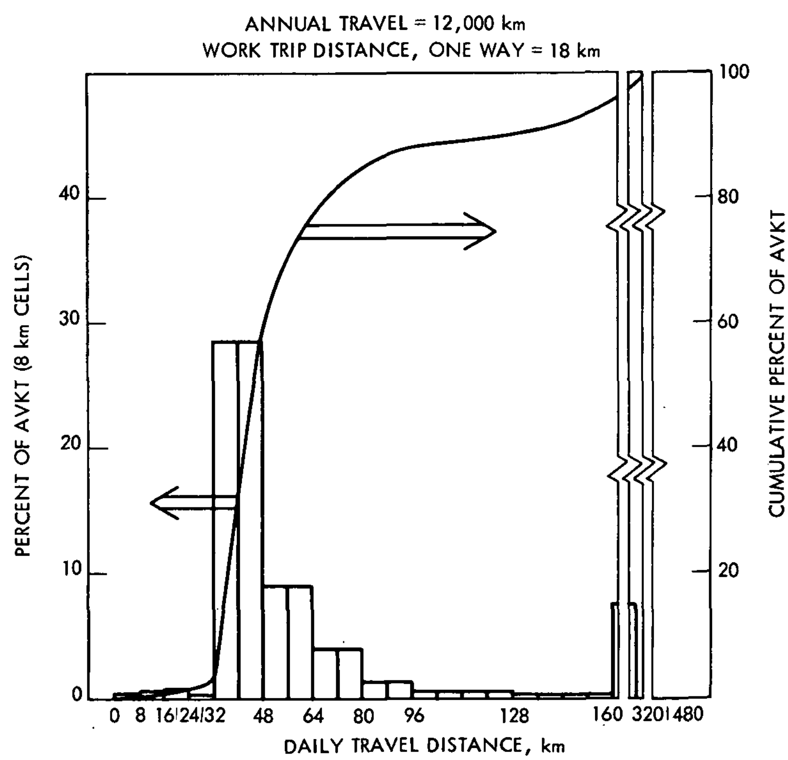


Figure 4-5. Distribution of AVKT, Mission I, Commuter Vehicle

2. Missions II and III - General Purpose

The primary purpose of these missions is general family travel. The NPTS data are not sufficiently documented to identify whether a vehicle was four-passenger or five-passenger; therefore differences in their annual travel patterns could not be estimated. It was assumed that these vehicles will have travel patterns in the 1990s similar to those in the latest NPTS, and annual statistics for these missions were developed on the same basis as previously described. The trends and projected annual travel for these missions are shown in Table 4-4.

Three travel patterns were developed (50th, 75th, and 90th percentile), characterizing the general purpose missions. Annualized daily travel for the three vehicles is shown in Figures 4-6, 4-8, and 4-10. The proportion of vehicle annual travel based on daily distances is shown in Figures 4-7, 4-9, and 4-11.

Examination of the annual travel pattern (Figure 4-10) shows that an HV with electric range on the order of 160 km could satisfy 90% of the daily driving requirements of a 90th percentile vehicle for this mission. An HV with this electric range could meet 80% of the AVKT for this mission or 23,603 km. Five-passenger vehicles are estimated to account for 698 x 10^9 km (1977) and 803 x 10^9 km (1990) annual fleet distance (see Figure 4-3). The potential for petroleum savings in these missions dominates the picture. The four-passenger vehicle is unattractive for HV development because it has severe volume limitations for the hybrid power train and batteries. The five-passenger HV is the most promising candidate for near-term development. The five-passenger general-purpose vehicle therefore has received the bulk of the conceptual design effort.

It is worth noting that a hybrid vehicle, even if improperly operated, does not suffer a sharp range cutoff such as occurs with electric vehicles. The HV is fully capable of traveling beyond its electric range while retaining its speed, acceleration, and gradeability performance. The penalty functions, petroleum savings per unit energy and petroleum savings per unit vehicle mass, will reflect the HV's usually inferior energy economy, but mobility is still retained.

Table 4-4. Annual Travel for Both General-Purpose Vehicle Missions

Annual Distance Percentile, %	Average Annual Travel, km		
	1969	1978	1990s
50	15,270	12,216	12,216
75	24,837	23,063	24,808
90	36,192	31,471	29,504

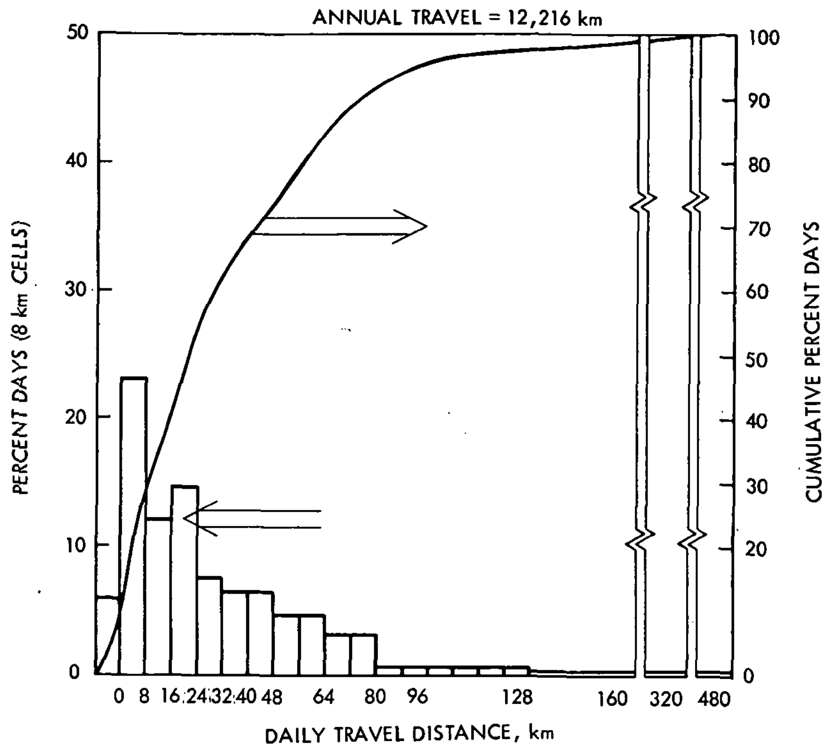


Figure 4-6. Annual Travel Pattern, Missions II and III, General-Purpose Vehicle

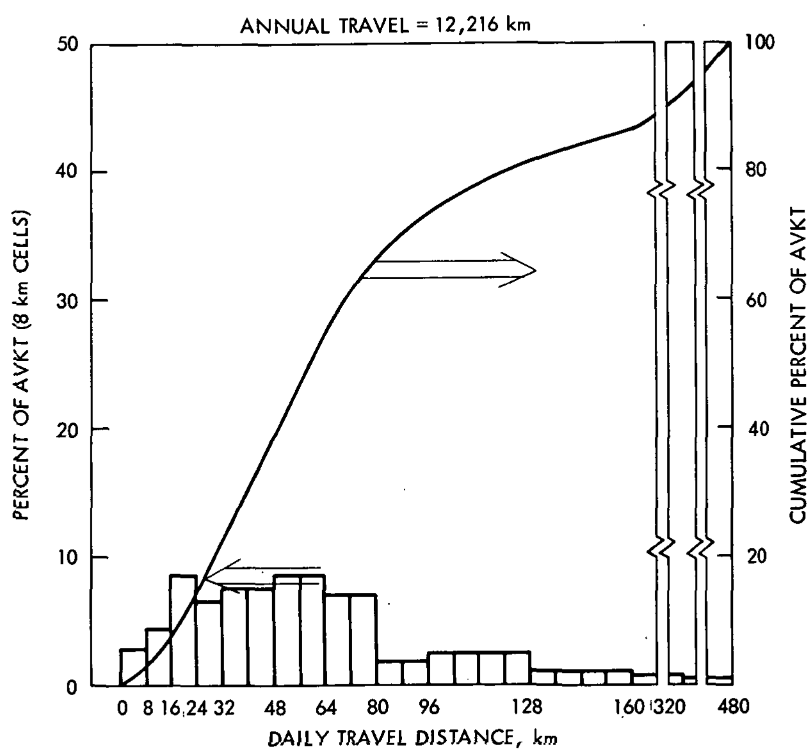


Figure 4-7. Distribution of AVKT, Missions II and III

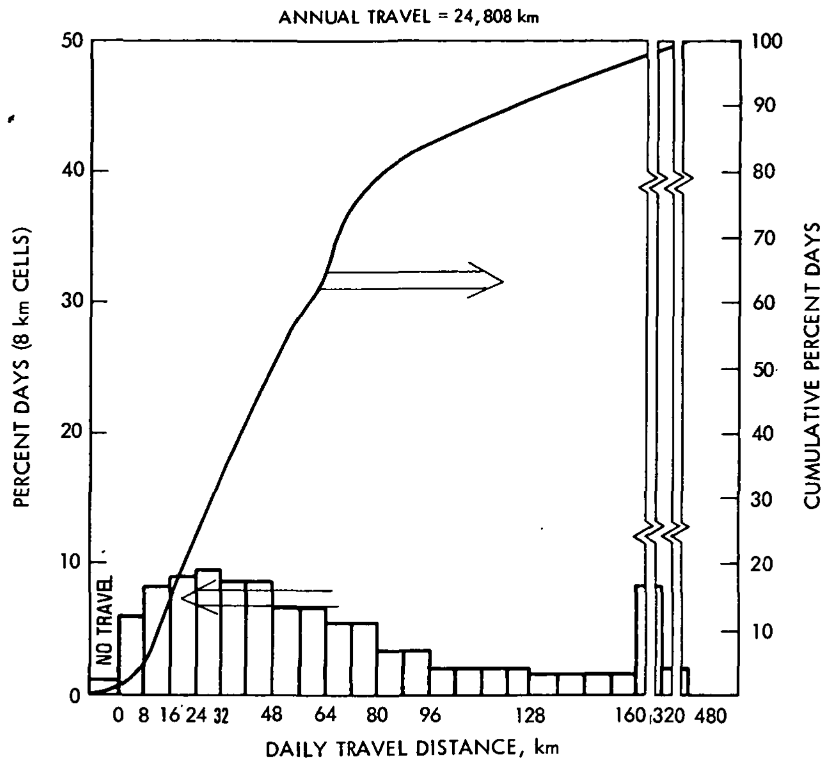


Figure 4-8. Annual Travel Pattern, Missions II and III

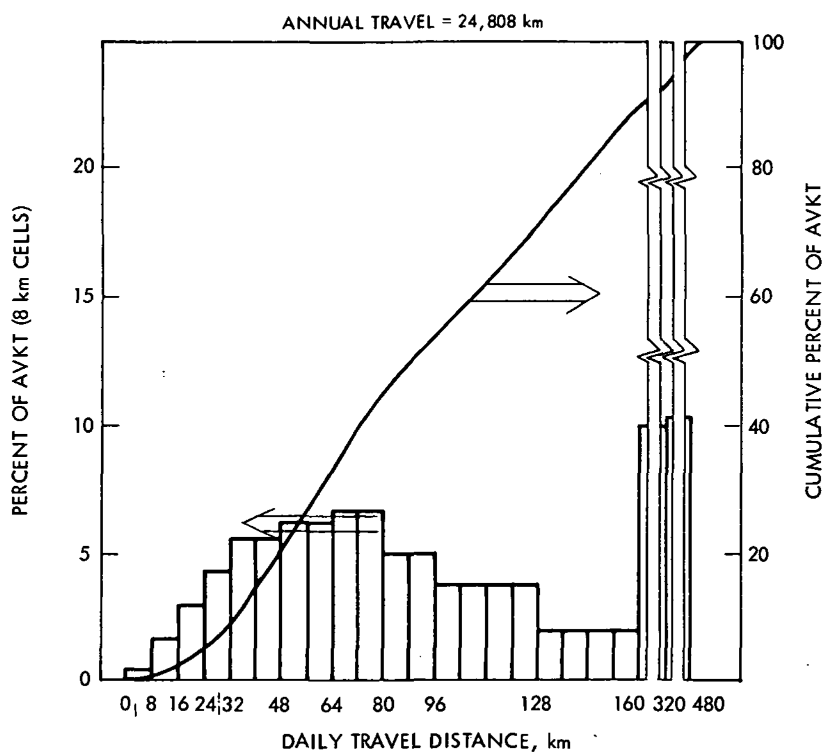


Figure 4-9. Distribution of AVKT, Missions II and III

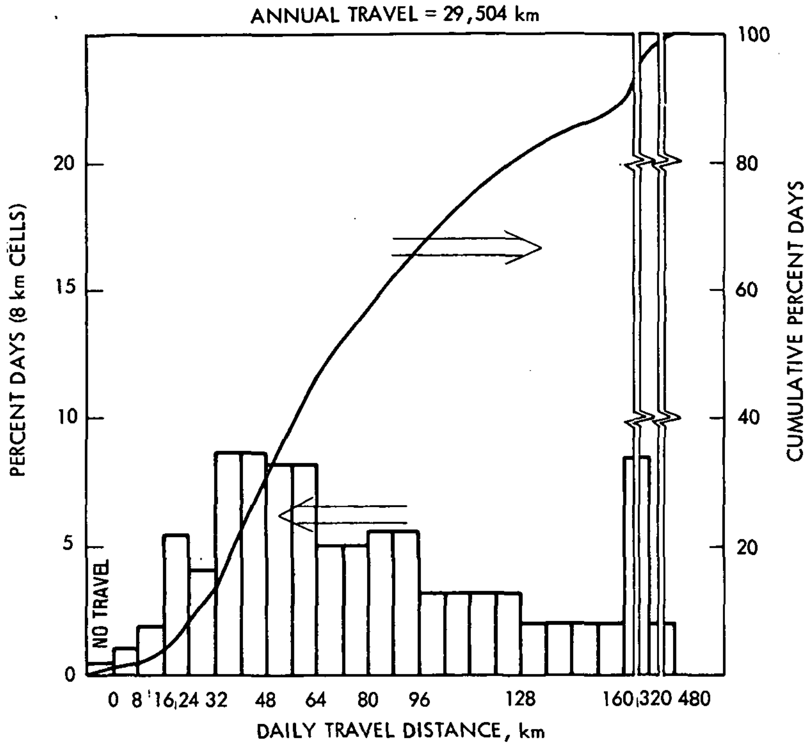


Figure 4-10. Annual Travel Pattern, Missions II and III

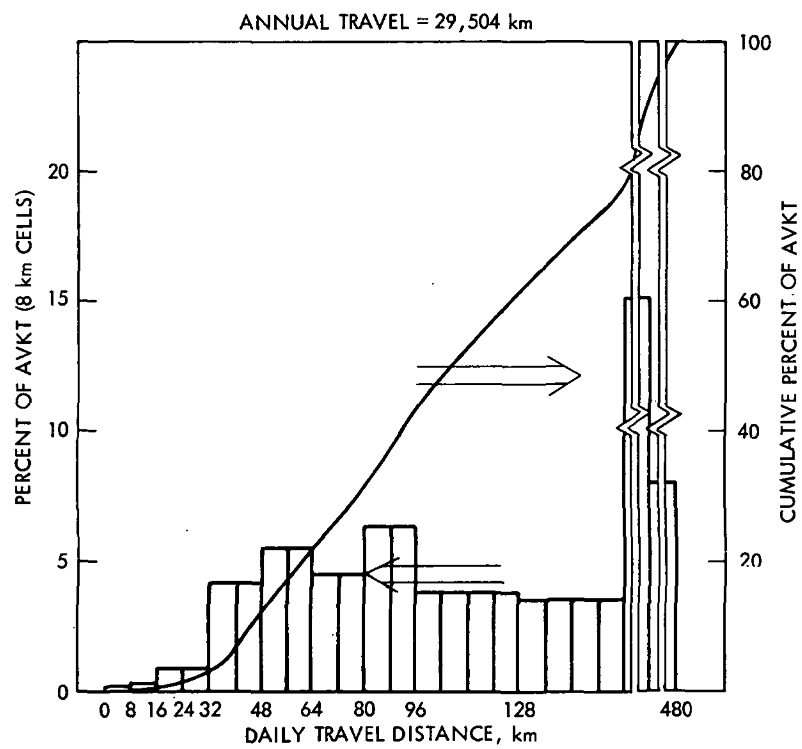


Figure 4-11. Distribution of AVKT, Missions II and III

3. Missions IV and V - Van Missions

Estimates of van sales in recent years have been developed by Oak Ridge National Laboratory (Reference 15). The sales of vans and all light-duty vehicles for the time period from 1978 to 1981 are shown in Table 4-5.

Because of the passenger and cargo space they provide, vans have become popular with consumers in recent years, and they constitute a large segment of commercial-vehicle fleets as well. It was estimated that a representative van mileage use distribution might be personal use/recreation vehicles, 20%; commercial/personal use, 40%; commercial use, 40%.

The HVA missions considered for vans were the commercial missions (utility fleets and independent businesses). These account for some 60% of the van use which can be split into fixed-route and variable-route use. In commercial application it was estimated that a typical van is driven about 250 days a year. The daily travel distribution and daily travel pattern for variable-route delivery vans are shown in Figures 4-12 and 4-13. Daily distribution and annual patterns for fixed-route delivery vans are shown in Figures 4-14 and 4-15.

D. TWENTY-FOUR-HOUR DRIVING CYCLES

In analyzing petroleum consumption, 24-h driving cycles were used. They were designed to describe accurately the driving environment in which a vehicle and its batteries must operate. The usable energy outputs of some batteries, notably high-temperature batteries and those with high self-discharge rates, are significantly affected by the amount of inactive time between recharges. The electric range of the hybrid vehicle is therefore affected by the self-discharge rate of the battery. In evaluating the performance of each battery, an effort was made to model daily driving to account for periods when the vehicle was parked. This was done by developing typical 24-h cycles for each of the daily driving distances. For example, a daily range of 60 km consisting of three trips of 20 km each, taken four

Table 4-5. Van and Light-Duty Vehicle Sales

Year	Van Sales, 10^3	Total Light-Duty Vehicles Sales, 10^6
1978	650	11.0
1979	580	13.5
1980	366	12.2
1981	338	10.7

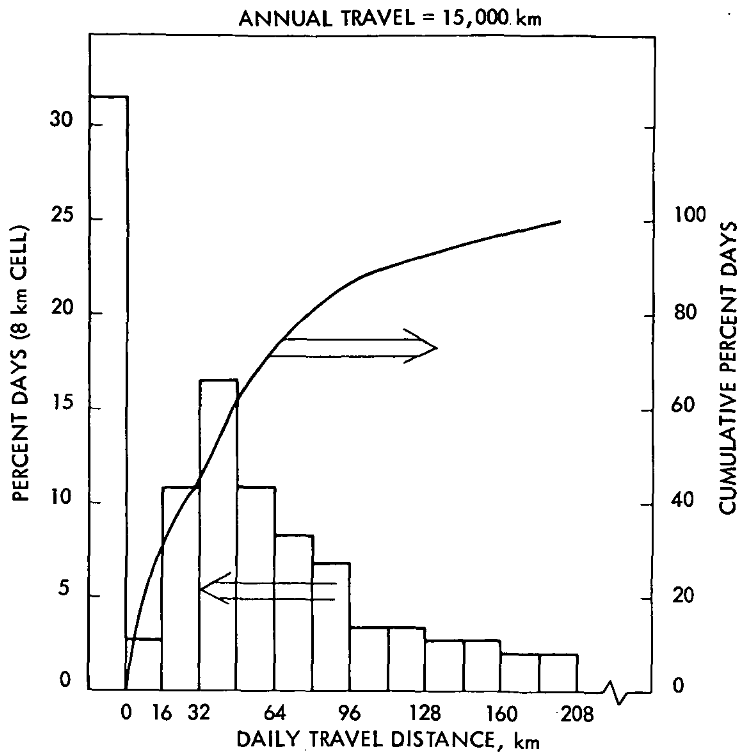


Figure 4-12. Annual Travel Pattern, Mission IV, Variable-Route Vans

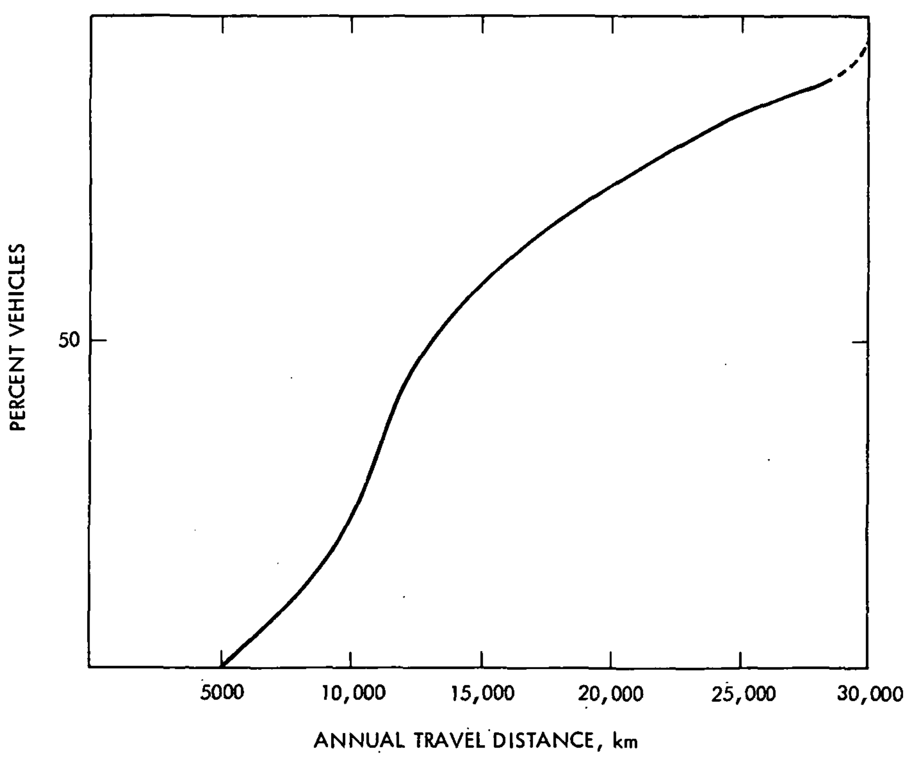


Figure 4-13. Distribution of AVKT, Mission IV, Variable-Route Delivery Van

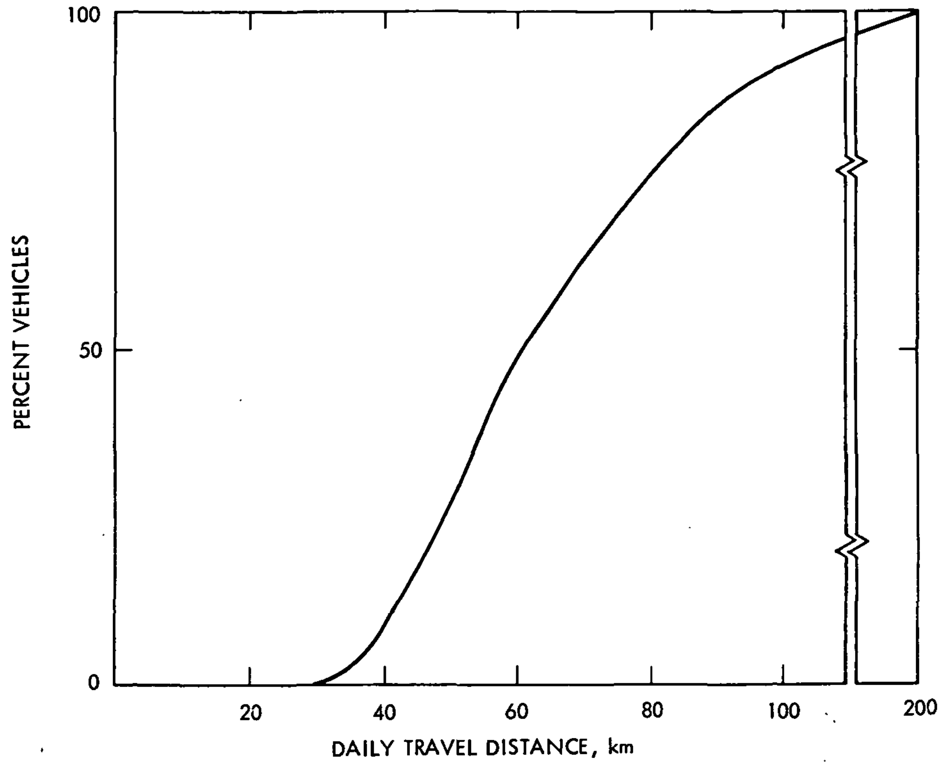


Figure 4-14. Daily Travel Distribution, Mission V, Fixed-Route Delivery Vans

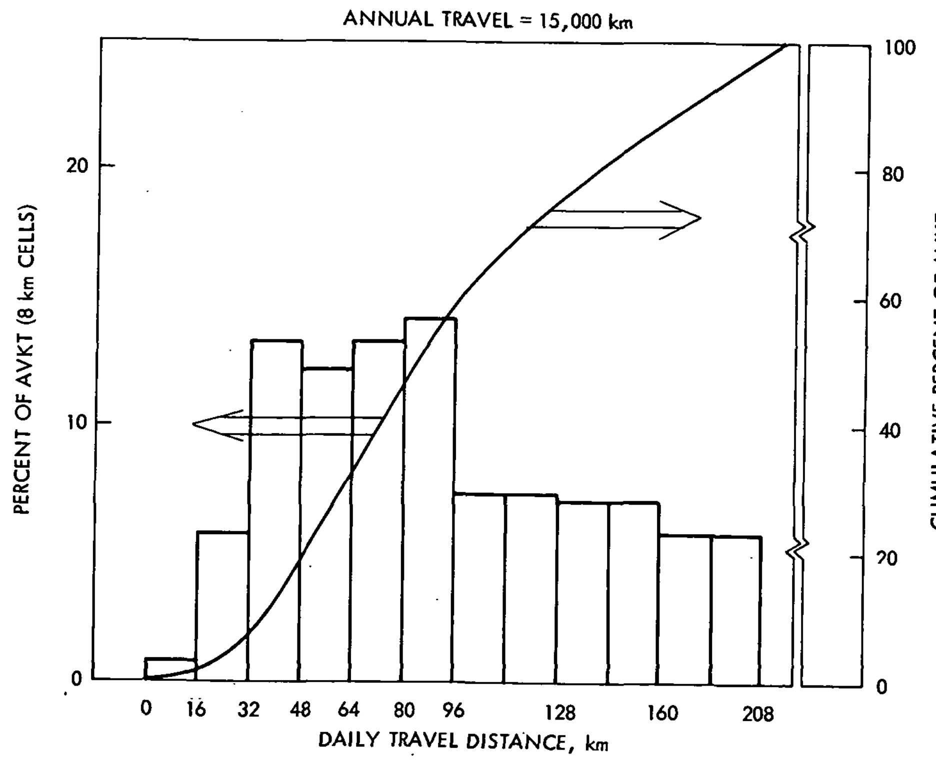


Figure 4-15. Distribution of AVKT, Mission V, Contribution of Daily Travel to Annual Vehicle Kilometers Traveled

hours apart was assumed. The 24-h cycle would therefore account for battery self-discharge occurring in the initial period before first use, between the two four-hour intervals between trips, and the time remaining before the nightly recharging. From NPTS data two distributions were developed:

(1) Starting time of the first trip.

(2) Mean time between trips.

Based on the trip frequency and trip length distributions used for developing daily travel distances, profiles of typical daily travel were developed for each of the 365 days in the year. These consisted of starting times for each trip and time the vehicle was parked.

For each daily travel distance (cell), daily travel profiles corresponding to the number of days that distance was driven in a year were developed. One of these was chosen to represent the cell and used in the vehicle performance simulation. The trip lengths were adjusted so that they could be represented by complete Urban or Highway Cycles or parts of Urban Cycles. Typical daily schedules are shown in Appendix B, in both tabular and graphical form.

Two daily distances were chosen to represent the fixed-route delivery vans, 60 km for vans traveling 15,000 km annually and 100 km for vans traveling 25,000 km annually. Because the delivery vans are used predominantly in urban areas, in all cases EPA cycles were used to develop the driving schedules. The schedules consist of complete EPA urban and highway cycles for both daily distances.

The daily travel for variable-route vans does not fall into a simple pattern. Because most of these vans are used in urban areas, the maximum distances traveled on any day were assumed to be 192 km. These cycles represent use either as utility vans or by independent businesses such as plumbing companies. The daily travel is characterized by substantial stop periods for the vehicle, a potentially important consideration for high self-discharge batteries. The distribution of daily distances for a typical van driven about 16,000 km annually is given in Appendix B.

Some trip lengths did not correspond to established EPA Highway or Urban Driving Cycles. For lengths shorter than the Urban Cycle (12 km), segments of the Urban Cycle were used to develop the schedules. These segments were selected by requiring that the segment end point be at zero vehicle speed. Complete cycles, either EPA Highway or Urban, were used whenever the trip lengths permitted. Thus, these schedules allow an accurate description of actual driving expected for hybrid vehicles for use in the HYVEC IV simulation described in Section V. Complete EPA Highway and Urban Driving Cycles are shown in Appendix B.

E. PERFORMANCE REQUIREMENTS

The HVs, when introduced into the U.S. transportation fleet, must fit into the existing transportation network. Safety and traffic flow properties must be similar to those of vehicles now in use to avoid major traffic

disruptions and ensure a satisfactory public reception. Performance requirements for the conceptual designs developed were required to be representative of fleet averages for the year 1990. The performance requirements specified were vehicle top speed, acceleration, and gradeability.[5]

All HV designs were required to provide speed, acceleration, and gradeability which were independent of battery SOC. It was assumed that drivers could not be expected to anticipate performance variations with changing battery SOC, and HV operations would be independent of battery state.

1. Speed

All hybrid vehicles described in this study are expected to operate on freeways where the capability to maintain average traffic speed is essential to safety. Solomon (Reference 16), in a study of accidents of vehicles on rural highways, found that accident involvement rates for low-powered vehicles were higher than the rates for high-powered vehicles. He concluded that accident involvement rates are a function of the difference between vehicle speed and the average speed of the surrounding traffic. Sustained speed and acceleration requirements for HVs, therefore, are similar to those conventional vehicles. A minimum sustained vehicle speed of 96 km/h (with no wind) for all of the automobile missions was specified.

Van/truck speeds were allowed to be slightly lower (90 km/h). Because of their larger size and greater visibility to other drivers, vans were assumed capable of operation at lower speed than the surrounding traffic without incurring an excessive rate of accidents.

2. Acceleration

Acceleration capabilities are critical design parameters because they determine the peak power-to-weight requirement for the vehicle. They are critical operating parameters because they affect both the safety of the vehicle and its impact on surrounding traffic. Acceleration capabilities were specified for:

(1) Freeway entry.

(2) Low-speed pass.

(3) Low-speed start.

(4) Four-second distance.

---

[5]Although these performance requirements were determined for 1990, the rationale for their development was previously derived (Reference 5). This reference treats the speed, acceleration, and gradeability requirements in detail.

The capabilities of currently available vehicles to accelerate from a stop to 88 km/h vary considerably with a range from a low of 9 s for high-performance cars to 23 s for some diesel-powered vehicles. A specification of 0-88 km/h in 18 s for automobiles and 22 s for vans and trucks was used on the basis of being reasonable, safe, and acceptable for the 1990 freeway entry.

A low-speed pass normally occurs in urban areas and is defined as the time required to overtake and pass slower moving vehicles. This maneuver, involving a change of speed from 30 km/h to 55 km/h, was specified in 6 s for automobiles and 8 s for vans and trucks.

The ability to gain speed from a complete stop is critical for acceptable traffic flow impact, especially in urban areas where signalized intersections are common. The required acceleration was 0-50 km/h in 7 s for automobiles and 8 s for vans and trucks. Another parameter of interest is the 4-s acceleration distance. For vehicles this was 25 m, generally the width of urban roadways. This is comparable to the performance of conventional vehicles. The 4-s distance requirement was relaxed to 20 m for vans and trucks.

3. Gradeability

Gradeability requirements are specified to ensure that vehicle performance on hills does not have an adverse impact on existing traffic. An estimate of grades on U.S. roadways (Reference 17) indicates that 96% of all mileage is at or below 6%.

Urban freeway grades rarely exceed 5%, and the gradeability (steady speed capability) was specified at a speed of 90 km/h for a distance of 8 km on a 5% grade. Freeway ramps and city streets have grades of up to 7%; for these, a speed of 50 km/h was specified for 0.4 km. Finally, vehicles must meet driveway grades of 30% at a speed of 5 km/h.

The performance requirements for hybrid vehicles are summarized in Tables 4-6a and 4-6b. They are independent of annual patterns and daily cycles because minimum performance requirements are determined primarily by the vehicle's operating environment. Vehicles operating in traffic and on highways must have traffic-compatible performance regardless of how often these capabilities are used.

These requirements were imposed on all HV conceptual designs. They determined peak power required by the vehicle when vehicle energy management strategy was specified. The freeway entry manuever and freeway gradeability requirements usually turned out to be the most demanding and also determined subsystem sizes and the electric motor, transmission, and heat engine ratings. This process is described in more detail in Section V. In optimizing the propulsion subsystem for petroleum savings, BMF (and therefore vehicle mass) are varied. <u>It should be emphasized that in this study all comparisons are made between vehicles with equal acceleration performance, gradeability, and passenger space</u>.

Table 4-6a. Minimum Speed and Acceleration Performance Requirements for Hybrid Vehicles

Performance		Automobile Missions	Van/Truck Missions
Sustained speed			
Freeway capability, km/h		96	90
Acceleration maneuver			
Freeway entry	(0-88 km/h), s	18	22
Low-speed pass	(30-55 km/h), s	6	8
Low-speed start	(0-50 km/h), s	7	8
Four-second distance	(from stop), m	25	20

Table 4-6b. Minimum Gradeability Performance Requirements for Hybrid Vehicles

	Grade, %	Distance, km
Gradeability (all missions)		
Freeway grades, 90 km/h	5	8
Freeway ramps and city streets, 50 km/h	7	0.4
Driveway grades, 5 km/h	30	0.1

SECTION V

POWER SYSTEMS

A. INTRODUCTION

This section presents a discussion of the heart of the hybrid vehicle, its power system. This system contains the drivetrain, power plant, drive axle(s), energy storage, and energy management system. These sets of components, their characteristics, and their interactions determine the performance of the vehicle, its energy use, efficiency, and suitability as a hybrid vehicle. The HV power system, therefore, received the most extensive analysis, and this section is the most detailed in the report. The HV configurations are discussed in both general and specific cases. The issue of energy management is treated (references are made to the earlier discussion on Design and Assessment in Section III), and the JPL HV Simulation Program for petroleum savings is briefly described. Results of the petroleum savings computations for HV conceptual design are presented, and their sensitivities to a number of vehicle parameters are calculated. (The utility functions used were also introduced in Section III.) Finally, conclusions and recommendations are presented. As discussed in Section IV, four- and five-passenger general-purpose vehicles offer the greatest potential petroleum savings. The limited available volume in the four-passenger vehicle makes it unattractive for a hybridized design, and the five-passenger vehicle has therefore received the bulk of the analysis. Results for the other vehicle types are presented in Appendices C and D.

Power train analysis within the HVA was used to select the vehicle configuration, the energy management strategy, and the BMF for the five-passenger general-purpose vehicle which could provide the greatest petroleum savings for the appropriate annual driving pattern. In all cases, the stated performance and petroleum savings of the HV will be in comparison to a conventional vehicle utilizing petrochemical energy (gasoline) and a spark-ignition engine.

B. HYBRID VEHICLE CONFIGURATION

1. General Descriptions

One means of categorizing HV configurations is by the number of driven axles. Typically passenger cars have one driven axle and one idle axle. A single-axle hybrid vehicle will employ both energy sources supplying power to one axle (Figure 5-1a). It is also possible to have two driven axles, either independently or jointly powered. A hybrid with two different energy sources, each independently supplying one axle, is called the split hybrid (shown in Figure 5-1b). The four-wheel-drive hybrid (Figure 5-1c) is similar to the split hybrid except that the two axles are interconnected so that energy from either source can be directed to either or both axles, as desired. Four-wheel drive is therefore possible, and two-wheel drive (involving either the front or rear axle) is also available with little difficulty. Although such hybrid vehicles can be designed, they have received very little analytical work. Limited analysis at JPL indicates that their

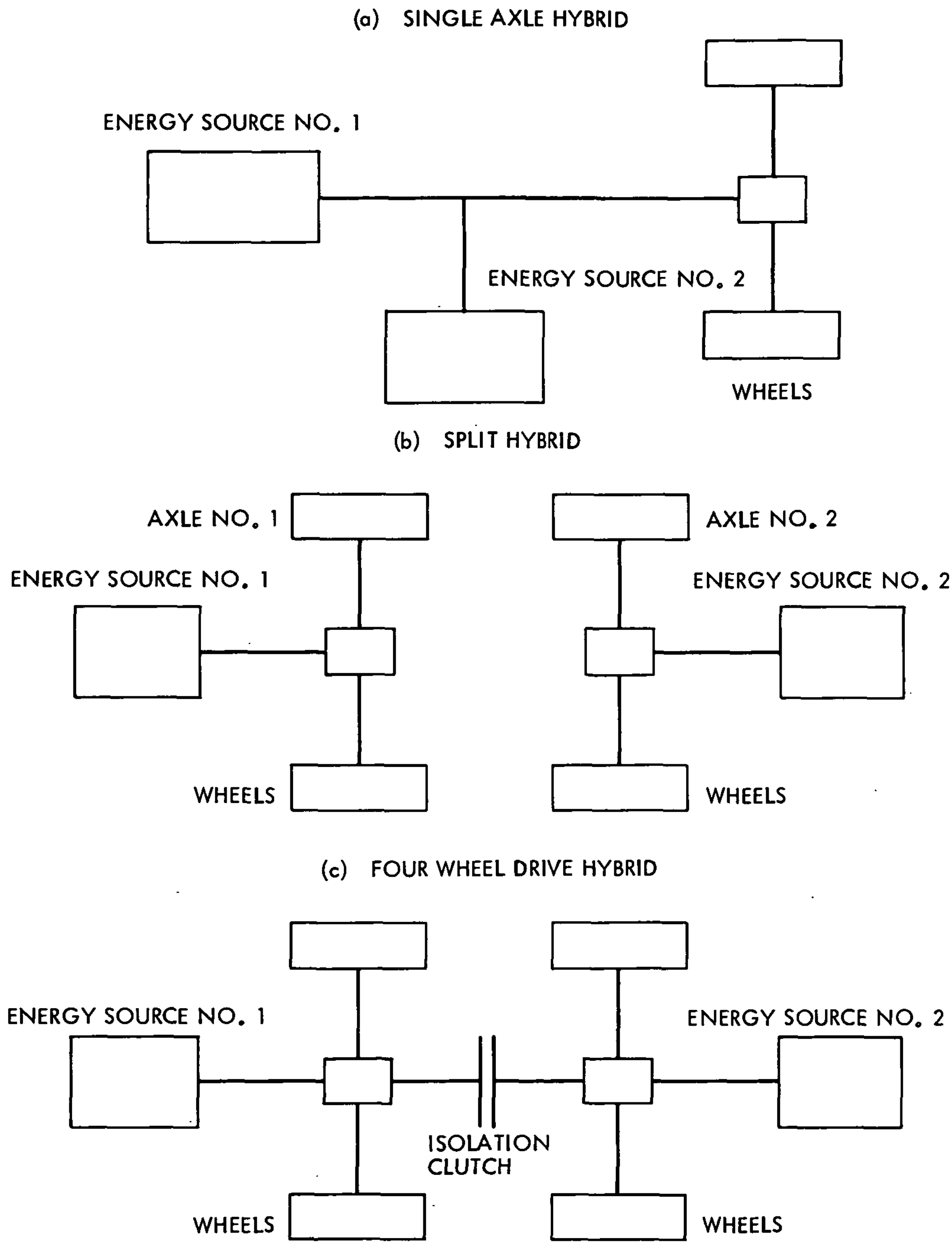


Figure 5-1. Categories of Hybrid Systems

energy requirements are very similar to the one-axle hybrid, and that the results for single-axle hybrids are applicable to two-axle hybrids with the exception of the drivetrain packaging. Because of this similarity and the added complexity of these more unusual configurations without any apparent added benefit, the HVA has concentrated on the one-axle hybrid and the subsequent discussion is limited to this configuration with only two exceptions. The general configuration of these hybrids are shown in Figure 5-2. This diagram shows all the components involved in virtually any single-axle hybrid. By deleting unwanted components, any of several hundred hybrid configurations can be developed.

The term "generator" as used in this report refers to either a dc generator or an alternator. The "motor" refers to any electric motor, ac or dc, and may, when necessary, include a transmission to better match the motor to the differential. A "power processor" on configuration schematics indicates a set of switches and controllers which regulate the input voltage of each component. "Accessories" refers to the fan, radio, air conditioner, power steering pump, windshield wipers, etc. Some accessories such as the fan are engine-mounted and used only when the engine is running. Others, such as the radio, are electrical so they depend on the power processor. Some may require continuous operation, such as the air conditioner. If the engine is operated in an on/off mode (that is, the engine is off when its power is not needed for traction), then the air conditioner obviously cannot be engine-mounted. In this case the air conditioner must be mounted on the motor and, because the motor must be running even if the car is stopped, a clutch must be included between the motor and the differential. If the engine is always on, the air conditioner, power steering pump, etc., could be engine-mounted or motor-mounted, depending on which is more efficient.

A gear box is a component of the transmission and it usually consists of one or more gear sets. If there is more than one gear set in the gear box, some means of shifting from one to another must be provided.

A transmission is a collection of components used to match the engine and/or the motor to the differential input. For example, a manual transmission consists of a clutch, a gearbox, and a gear shift lever. An automatic transmission typically is made up of a torque converter, a gear box, and a control system for shifting the gears. The details of transmissions will vary but the requirements to match the engine or motor speed to the wheels are the same for all.

One-axle hybrids can be subdivided into two main groups, series and parallel. In series hybrids, power from the engine is converted into electric power through a generator to charge the battery or to drive the motor. In parallel hybrids, the engine power is fed directly to the wheels. The motor can also power the wheels. There is a third category, the series/parallel, in which some engine power is converted to electricity and the remainder is fed directly to the wheels. Another type of series/parallel hybrid can be changed from series to parallel and back again.

The first six configurations are for the electric drive systems. Configuration 1 (Figure 5-3) is the traditional series hybrid. All engine power is converted to electric power by the generator and is reconverted to mechanical power by the motor. This double conversion results in relatively

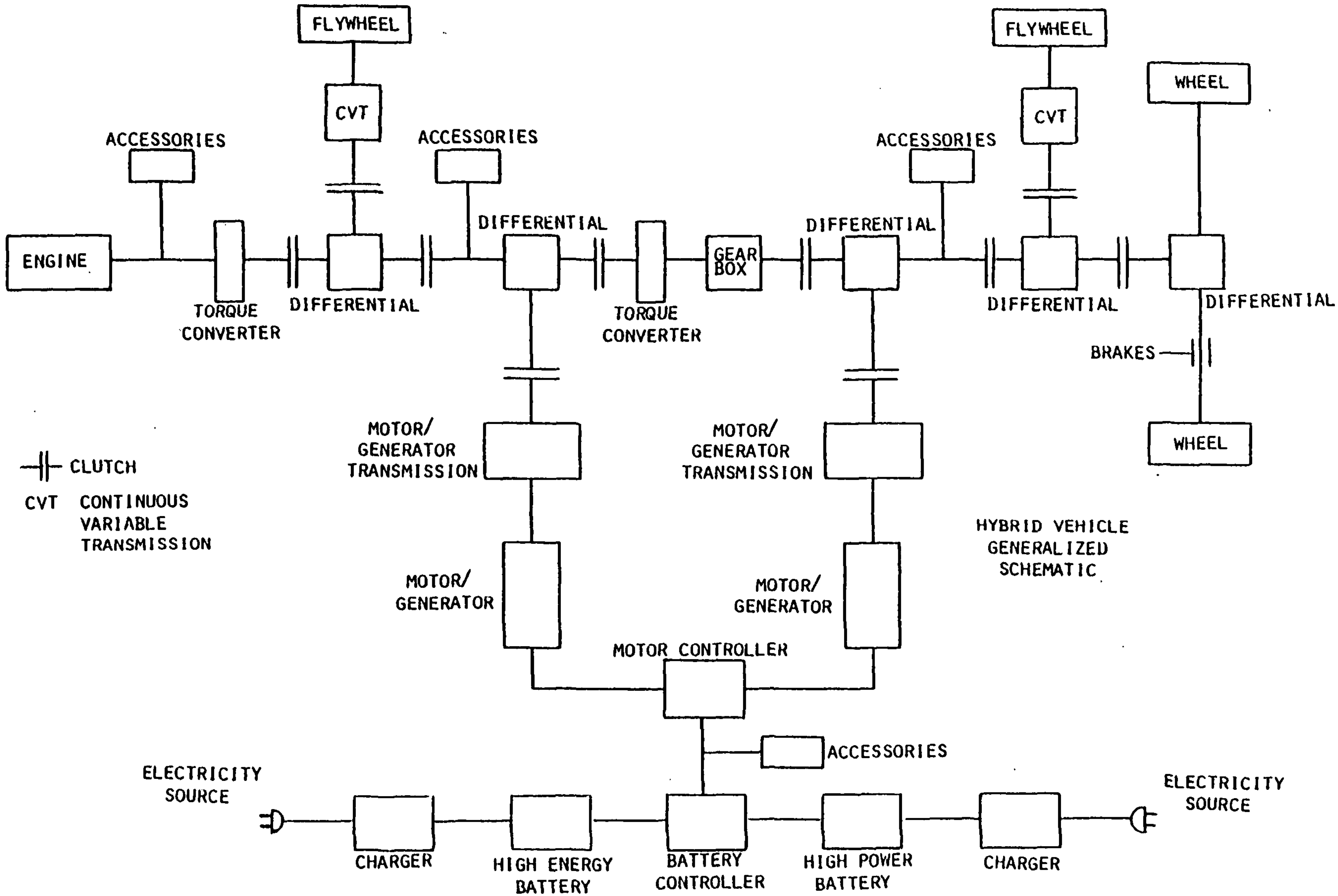


Figure 5-2. Generalized Single-Axle Hybrid Schematic

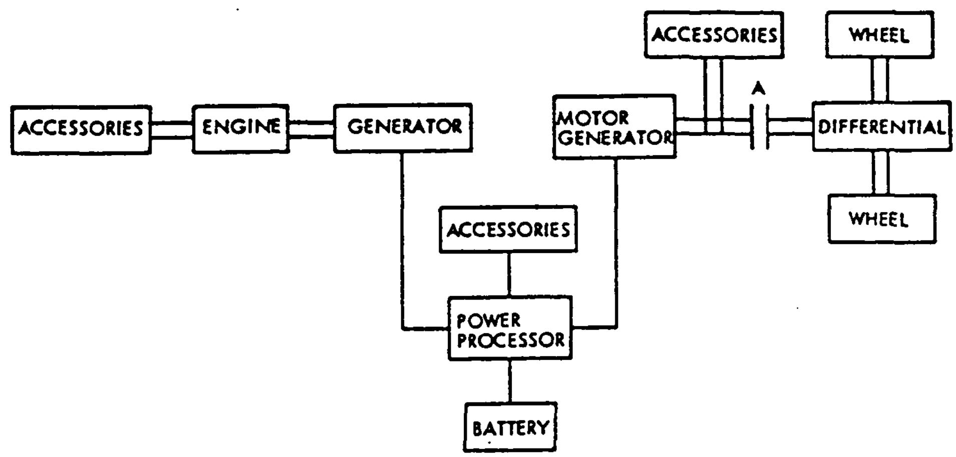


Figure 5-3. Configuration 1

low driveline efficiency, particularly at light loads. Since the components are in series, individual component efficiencies are multiplied to give the overall system efficiency. If regenerative braking is used, the motor in Configuration 1 must be a motor-generator.

Configuration 2 (Figure 5-4) is similar to Configuration 1, but the motor cannot generate electrical power and four clutches are included to control the power flow. In this configuration, the batteries can be used to drive the car by closing Clutch C and opening Clutch B. As long as Clutch B is open, this configuration is functionally equivalent to Configuration 1. There are, however, two advantages to having Clutch B in the system. The first is that when the batteries are discharged, the engine can drive the car directly with minimum loss; the second is that during regenerative braking the generator is used rather than a motor-generator as in Configuration 1. Clutch A is an overrunning clutch which allows the engine to drive the car but prevents it from absorbing power from the drivetrain. Clutch D is optional and is used to eliminate generator windage and bearing losses.

For Configuration 3 (Figure 5-5), in addition to the differential that serves the wheels, one is introduced which includes brakes on each of its three shafts so that power flow can be controlled. Also in this configuration, a single motor-generator is used in place of the separate units in Configuration 1 and 2. The batteries can be used to drive the car if Clutch A is open, Clutch B is closed, and differential Shaft 1 is locked by a brake. Power flows from the batteries to the motor-generator to Shaft 2 of the differential and out Shaft 3 to the wheels. When the batteries are discharged, Clutch A is closed so that engine power flows through Shaft 1 to Shaft 3 and to the wheels. By locking Shaft 3, closing Clutch A, and opening Clutch B when the car is standing still, the engine can be used to recharge the batteries and drive the motor-mounted accessories. It is possible to have the engine charge the batteries and drive the car at the same time, or the batteries and the engine can supply power to the car simultaneously. This configuration is therefore quite flexible. In addition, the speed of Shaft 3 can be varied independently from Shaft 1 (within limits) by using the motor-generator and Shaft 2 as a variable speed input to the differential. The differential operates as a continuously variable transmission (CVT).

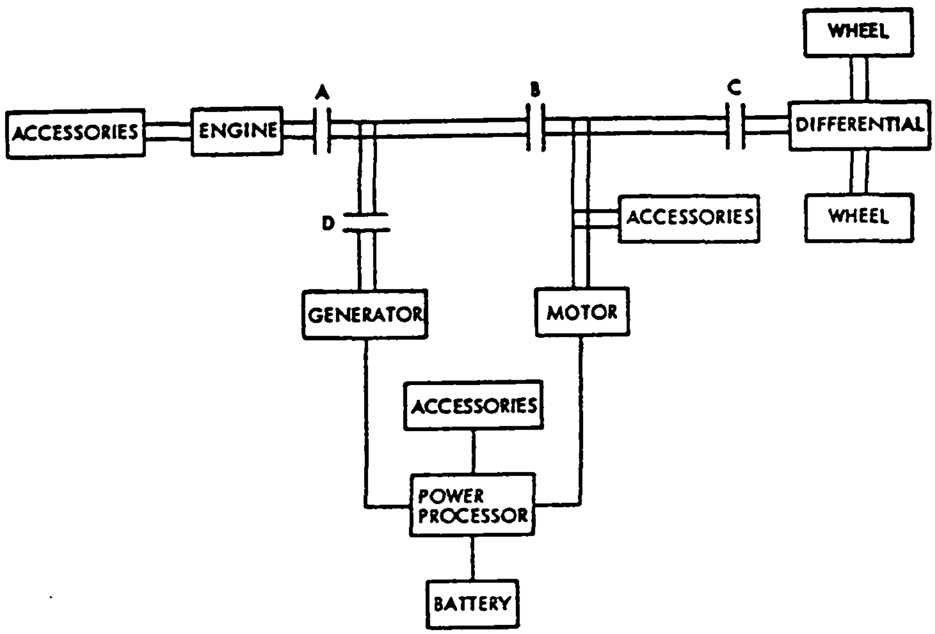


Figure 5-4. Configuration 2

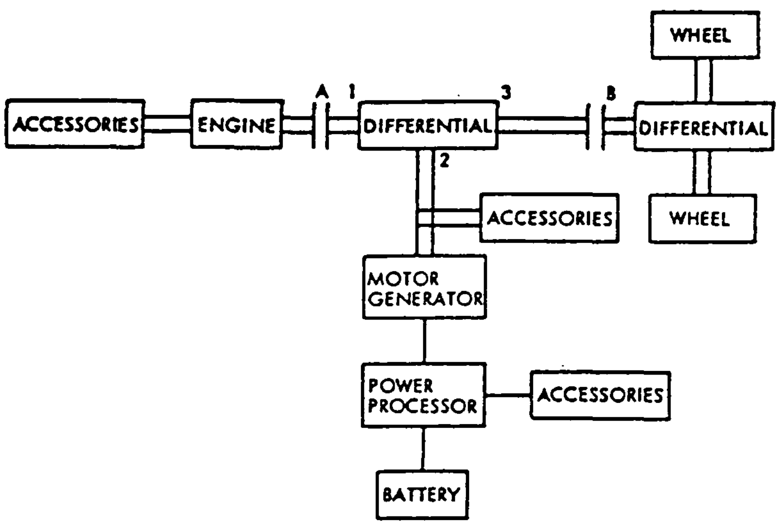


Figure 5-5. Configuration 3

The motor-generator in Configuration 4 (Figure 5-6) is a double-ended unit rather than the single-ended units used earlier. Functionally, Configuration 4 is the same as Configuration 2 without Clutches B and D and with the overrunning Clutch A replaced by a conventional clutch. The result is a smaller, simpler system, having greater drivetrain inertia and with windage and bearing losses rather than clutch losses.

Configuration 5 (Figure 5-7) is the same as Configuration 4 except that the generator and motor are separate units joined by a clutch. The choice of Configuration 4 or 5 would depend on unit costs, weights, and the relative efficiencies of separate units vs an integrated motor-generator.

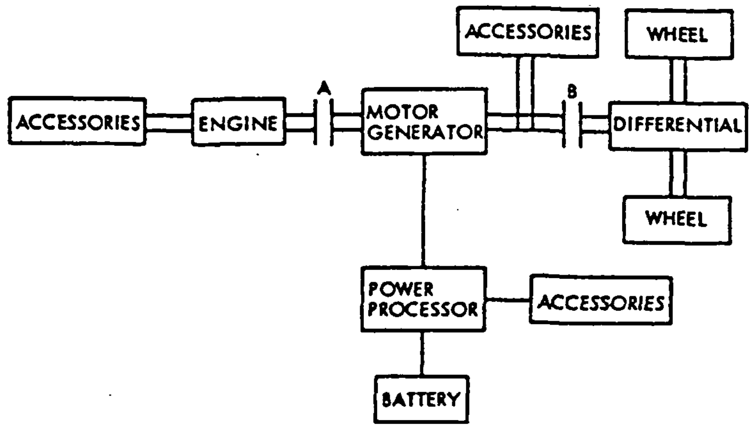


Figure 5-6. Configuration 4

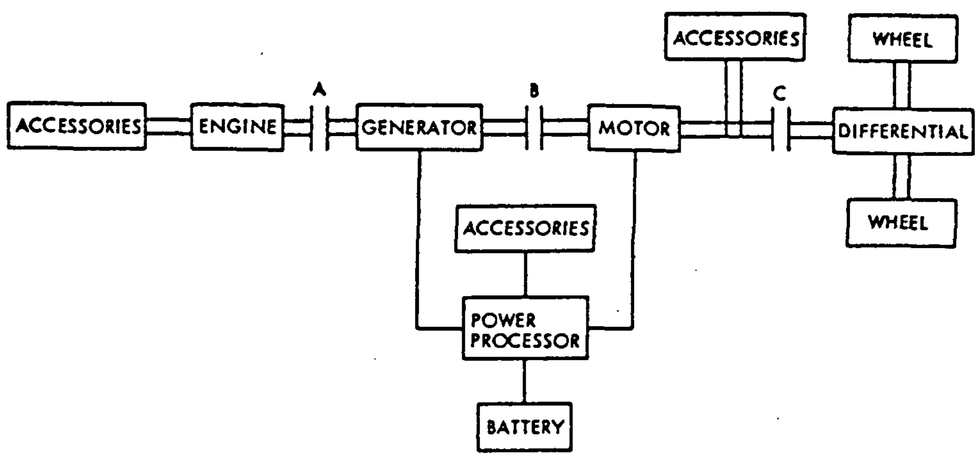


Figure 5-7. Configuration 5

One problem with Configuration 2 is that if the batteries are discharged and the engine is driving the vehicle, there is a minimum vehicle speed which must be maintained (as in a conventional car with a manual transmission in direct drive). If the car slows below the minimum speed, it would be necessary to open Clutch B and run the car as a series hybrid. Engine power would go to the generator, then the motor, and finally to the wheels.

In Configuration 6 (Figure 5-8), a differential is used to provide a wider range of vehicle speeds for a given range of engine speeds. When the engine is operating and the vehicle speed is high enough, Shaft 2 is locked so that engine power goes directly to the wheels. If the vehicle speed is too low, part of the engine power goes through the generator to the motor which provides a variable speed input to the differential so that engine operates at a higher speed than it would otherwise. Because only part of the engine power goes through the relatively inefficient motor-generator path, the overall efficiency of the configuration will be higher than that of Configuration 2 for the same conditions.

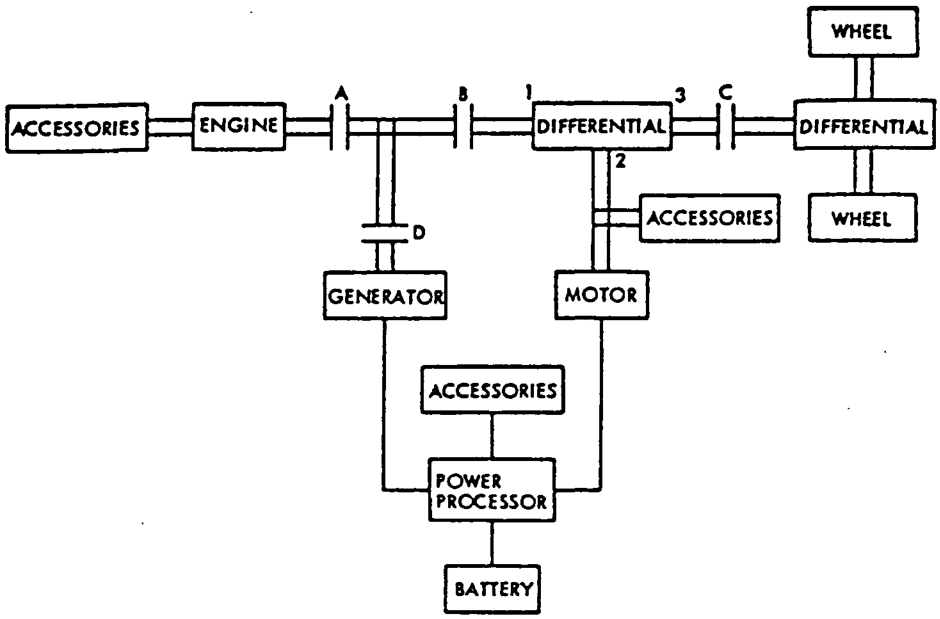


Figure 5-8. Configuration 6

In the foregoing discussion, it has been assumed that the battery could accept all power available during regeneration. In reality, this may not be possible. Charging characteristics of many batteries are poorly understood, and frequently the rate at which energy can be efficiently accepted by a battery is lower than the rate at which it can be extracted. (The notable exceptions to this statement are lead-acid, nickel-iron, and nickel-zinc batteries below 90% SOC.) During normal driving, the rate at which energy is dissipated during deceleration is typically as high as the rate at which energy is used during acceleration. This means that acceptable battery recharging rates during regenerative braking may impose a more severe limitation on the system than acceleration rates. If all or at least a reasonable fraction of the available regenerative braking energy is to be used, the batteries must be sized for the recharging load rather than the discharging load (or some other system must be included which does not have these recharging limitations). One, but not the only, possible system is the flywheel. While it is not suitable for long-term energy storage because of windage, bearing, seal, and gear losses, it can be used as a buffer between the car and the batteries. It can absorb power at a high rate from the car and release it to the battery at a lower rate, closer to the battery's absorption capacity. In reality, safety considerations will dictate the amount of regenerative energy accepted by the battery. A four-wheel braking system will be required for all vehicles.

Configurations 7 through 13 show the application of a flywheel buffer to Configurations 1 through 6. Two versions, Configurations 7 and 8, of the series hybrid Configuration 1 are shown. One places the flywheel next to the engine and the other places it at the motor-generator. In Configuration 7 (Figure 5-9), the engine can be readily used to charge the flywheel and to supply power to the generator. However, if regenerative braking is used, the power must pass through the motor-generator, the power processor, and a second

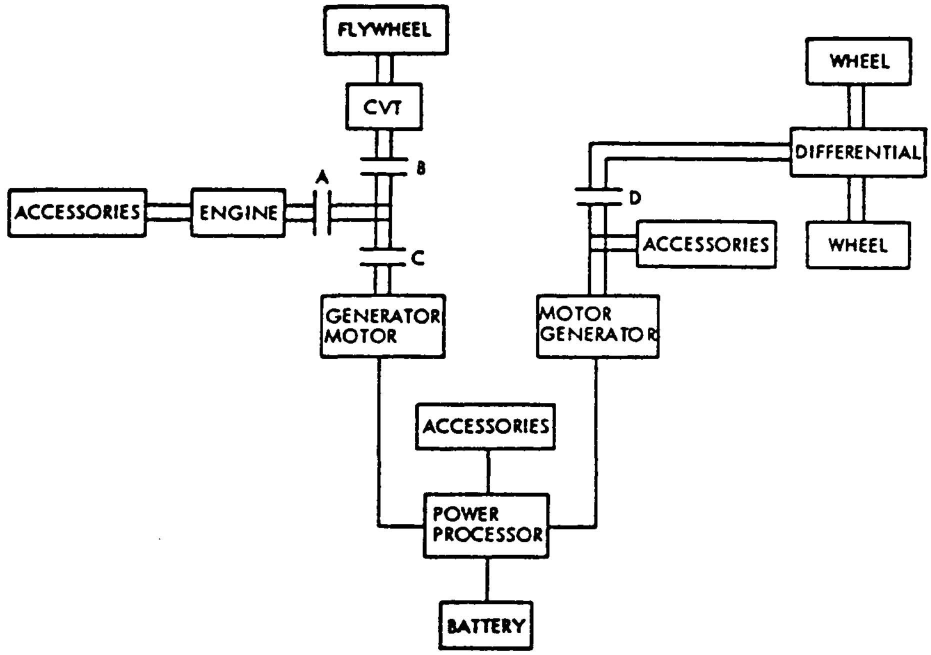


Figure 5-9. Configuration 7

motor-generator to the flywheel. Very little braking energy would reach the flywheel and even less would reach to the battery. A configuration employing two motor-generators, a power processor, and a CVT in series guarantees very poor efficiency. In Configuration 8 (Figure 5-10), the flywheel is moved to the motor shaft. Regenerative braking power reaches to the flywheel directly through the CVT. However, if engine power is used to charge the flywheel, it must now pass through the generator, the power processor, and the motor as well as the CVT. The generator is used instead of the motor-generator in Configuration 7.

If the flywheel and CVT are added to Configuration 2, then the result is Configuration 9 (Figure 5-11). In this configuration, engine power can charge the flywheel directly and regenerative braking energy also has a direct path to the flywheel. Both engine and flywheel power can supply the generator and then the battery or motor. Five clutches are needed, but Clutch B is optional, depending on the relative losses of the clutch vs the losses in the generator and its inertial effects. Clutch D could be eliminated if the CVT has the ability to decouple the flywheel from the rest of the drivetrain. Some CVTs have this capability; others do not.

Configuration 10 (Figure 5-12) is the same as Configuration 3 with the addition of the flywheel and CVT. A major problem in Configuration 3 is that if the battery is dead and the car has stopped or is moving slowly, it is difficult to accelerate because the engine would be in direct drive with the wheels. With the flywheel and CVT, the low-speed operation could be handled using them only and running the engine at a higher speed. If the flywheel were discharged, the vehicle would have to stand until the engine had charged it sufficiently to start the car. (This would involve perhaps a 30-s time period because the flywheel could be charged much more rapidly than the

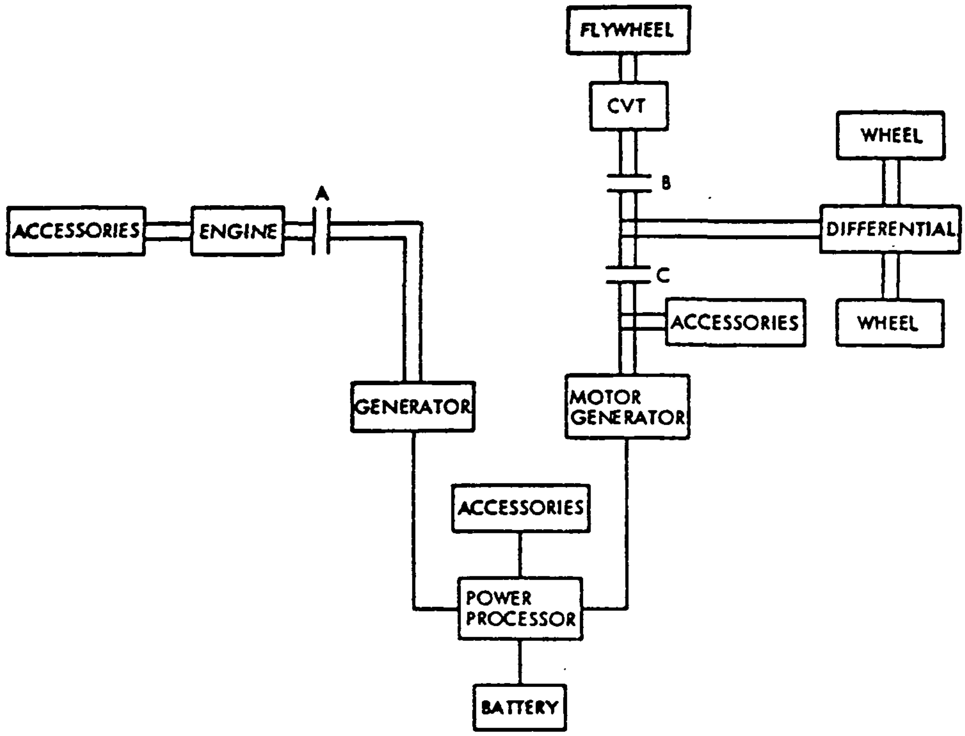


Figure 5-10. Configuration 8

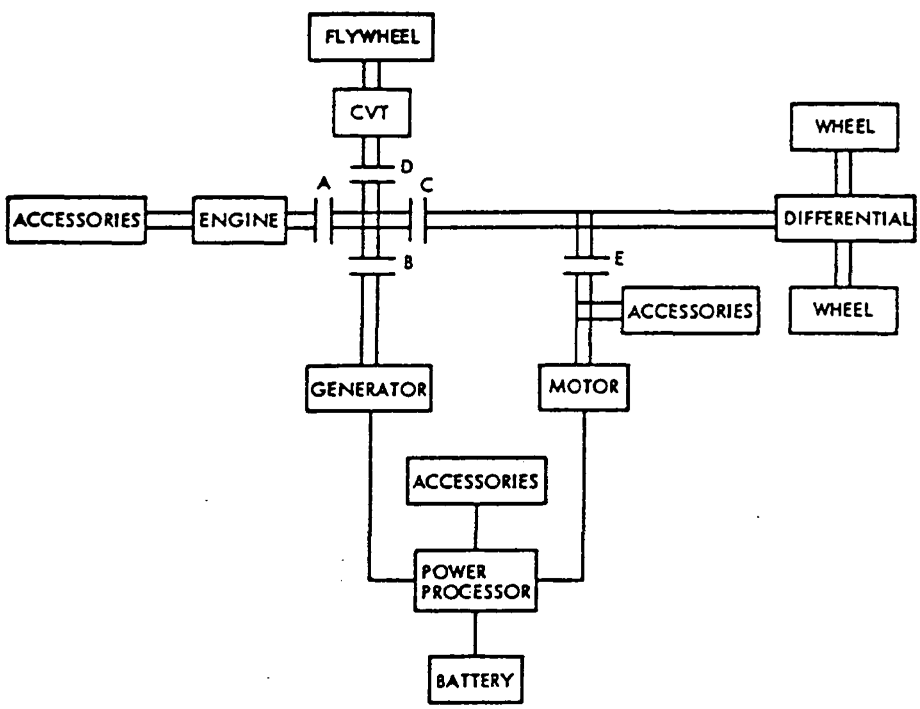


Figure 5-11. Configuration 9

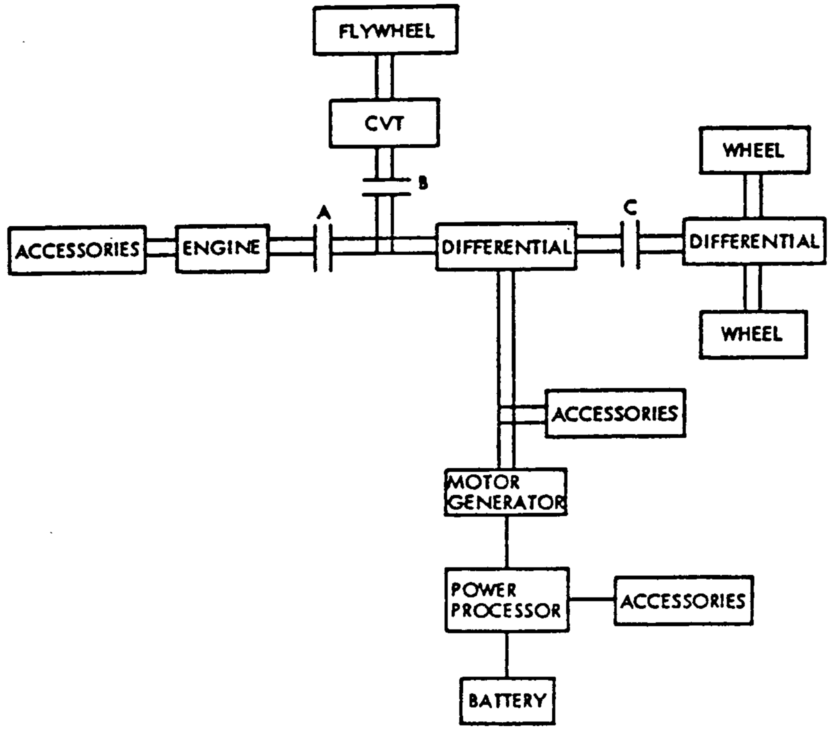


Figure 5-12. Configuration 10

batteries.) Once the engine starts, it can charge both the flywheel and batteries. The differential in both of these configurations could be replaced by a gear set. The resulting configurations would be functionally the same as Configurations 4 and 11 (the latter is shown in Figure 5-13). The difference is that Configurations 4 and 11 use a double-ended motor-generator instead of the single-ended unit in Configurations 3 and 10. The problem of low-speed driving and accelerating from a stop would be the same for Configurations 3 and 4. The advantages of the flywheel would be the same for Configurations 10 and 11.

In Configuration 12 (Figure 5-14), both the motor and generator are double-ended. The engine and flywheel can be connected by direct drive to the wheels for efficient cruise or regenerative braking. The engine can charge the flywheel directly. In addition, if the batteries are discharged, the motor and generator can be used as an electric transmission. The flywheel can be used to move the car, start the engine, or act as a buffer for the battery. Functionally, this configuration is the same as Configuration 9 and it is the same as Configuration 5 with the exception of the flywheel and CVT.

Adding a differential to Configuration 9 results Configuration 13 (Figure 5-15). This is the most complex and most flexible of the configurations presented so far. The main difference between the next two sets of configurations and the earlier ones is the presence of a transmission in the system. It previously was stated that a transmission could be placed at the motor output to serve only the motor. In this case, it serves both the motor and the engine. This transmission also differs from the clutches used

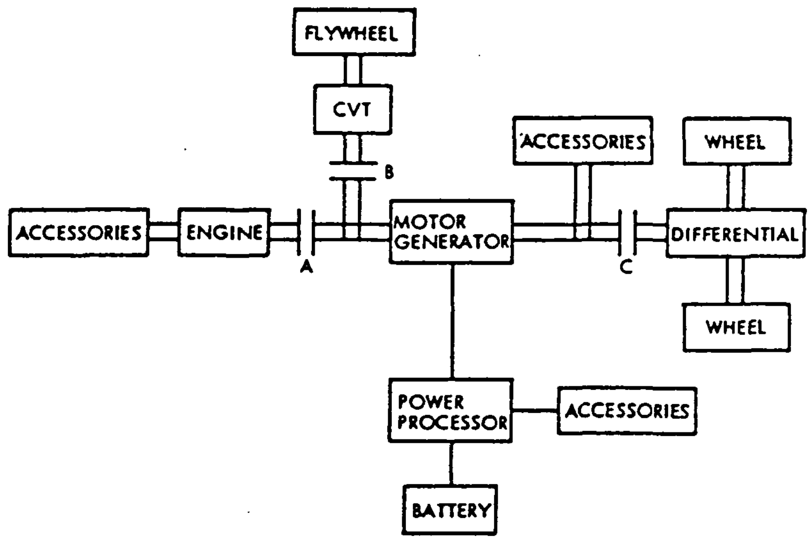


Figure 5-13. Configuration 11

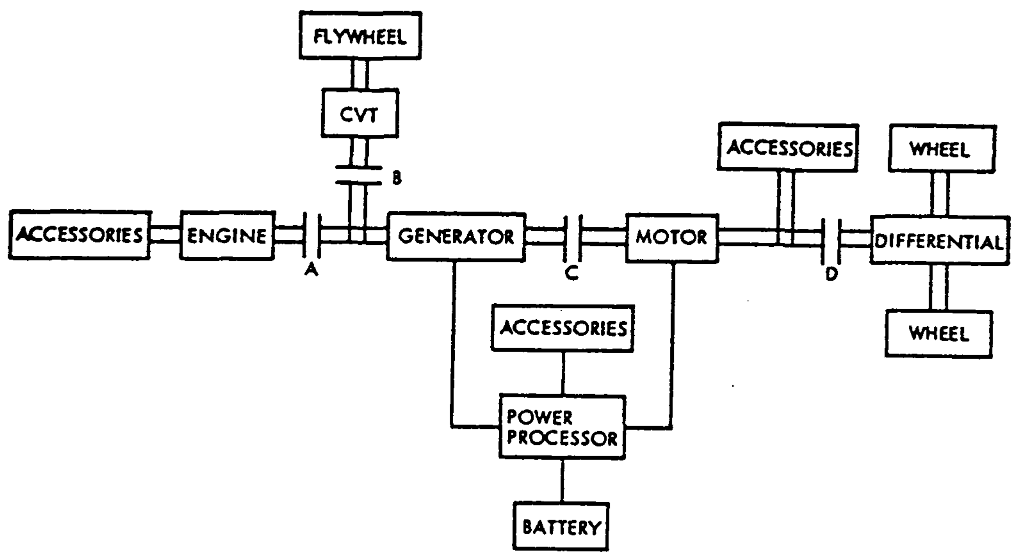


Figure 5-14. Configuration 12

in earlier configurations because it changes speed and/or torque over some specified range, either continually or stepwise. The clutches were assumed to be either open or closed, but never slipping. The transmission used in this case has two input/output shafts while the differential used in earlier configurations had three.

All configurations presented so far are a form of a parallel hybrid without a transmission (except for Configurations 1, 7, and 8 which are true series hybrids). Opening Clutch B in Configurations 2, 5, and 6 allows

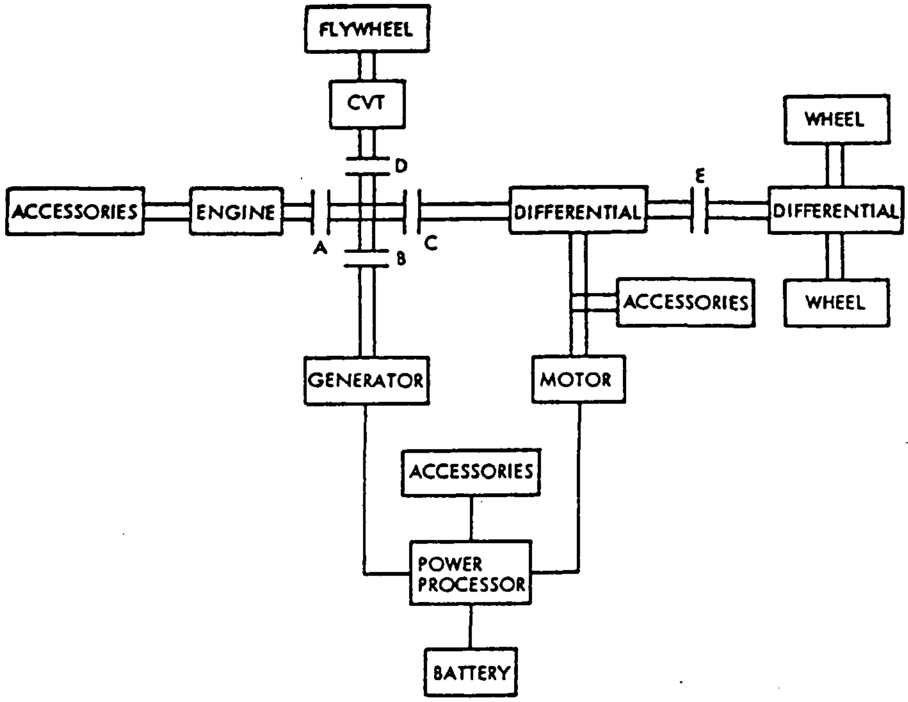


Figure 5-15. Configuration 13

operation as series hybrids while closing it allows operation as parallel hybrids. (This is true of the flywheel versions as well.) Configurations 3 and 4, as well as their flywheel versions, are true transmissionless parallel hybrids. They cannot be operated as series hybrids at all.

The classic parallel hybrid is shown in Configuration 14 (Figure 5-16) with a transmission between generator and motor. This configuration is similar to Configuration 2 although the transmission replaces Clutch B and Clutch C is in the motor output leg of the system. This clutch allows the motor to drive the accessories without feeding power into the output of the transmission. In some transmissions, this power could be important; in others, it would not be needed and Clutch C could be omitted.

Configurations 15 and 16 use a single motor-generator but the location in each case is different. In Configuration 15 (Figure 5-17), it is between engine and the transmission. The motor output passes through the transmission to the wheels, eliminating the need for a transmission on the motor output shaft. Regenerative braking power must pass efficiently through the transmission in the reverse direction. Some transmissions, such as a slipping clutch, have the same efficiency regardless of the direction of the power flow while others, such as the conventional automatic transmission, have high efficiency only in one direction and a very low efficiency in the reverse direction. Not only is the efficiency of a conventional automatic transmission low in the reverse direction, but its power capacity (the ability to transmit power) is also low. Configuration 16 (Figure 5-18) with the motor-generator between the transmission and the wheels does not need the same type of transmission but may require a gearbox on the output shaft of the

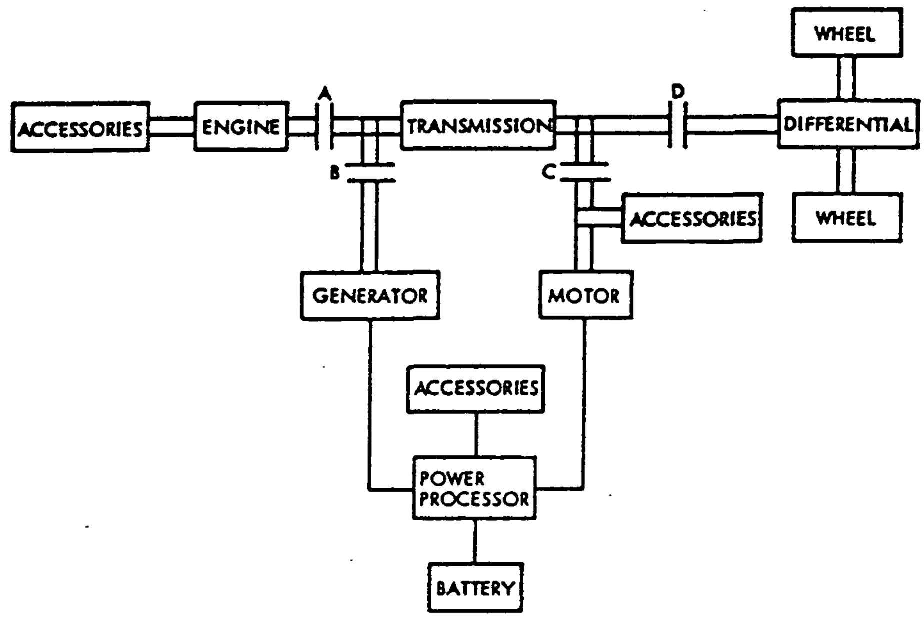


Figure 5-16. Configuration 14

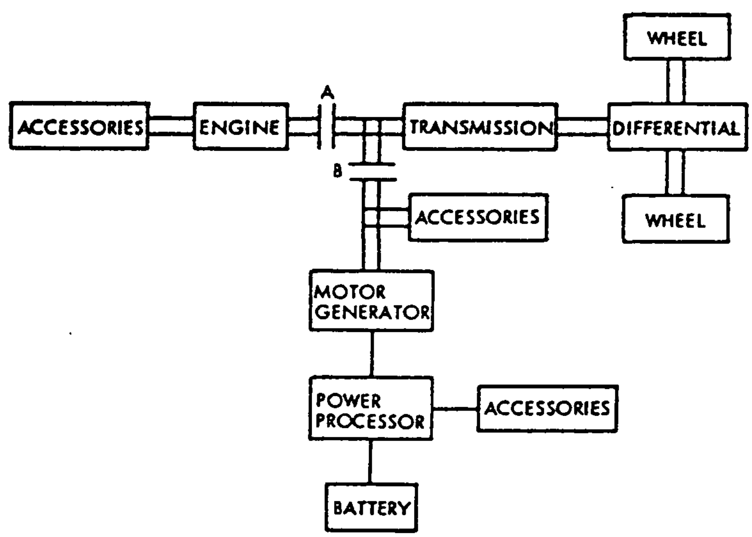


Figure 5-17. Configuration 15

motor. In this configuration any power generated by the engine to recharge the batteries must pass through the transmission as well as the generator. An extra clutch is necessary so that the engine can drive the accessories on the motor output shaft whenever the battery is discharged and the car is stopped.

The addition of a differential to Configuration 14 results in Configuration 17 (Figure 5-19). Because of the differential, there is no need for Clutch D used in Configuration 14. The transmission handles coarse speed changes while the differential, by using the motor for control, can fine tune the speed. As a result, the engine speed is restricted to a reasonably narrow range for best fuel economy.

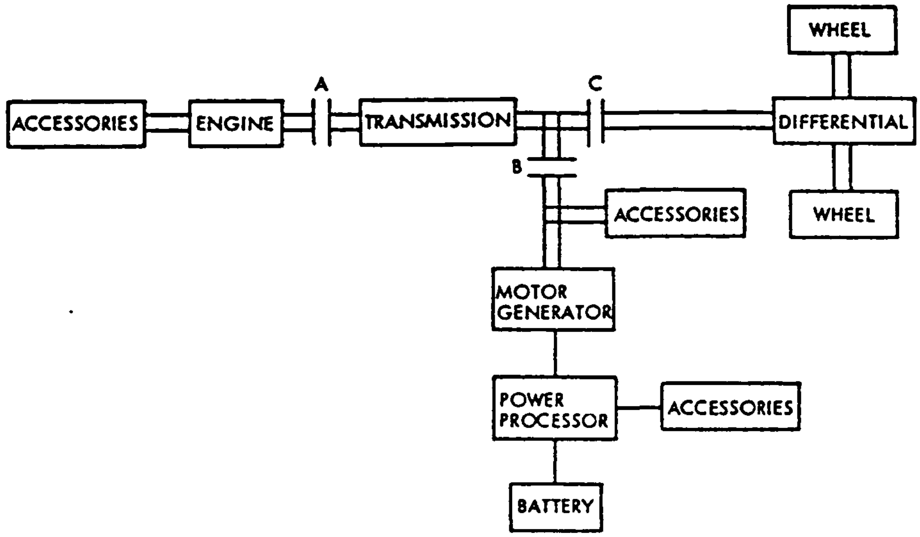


Figure 5-18. Configuration 16

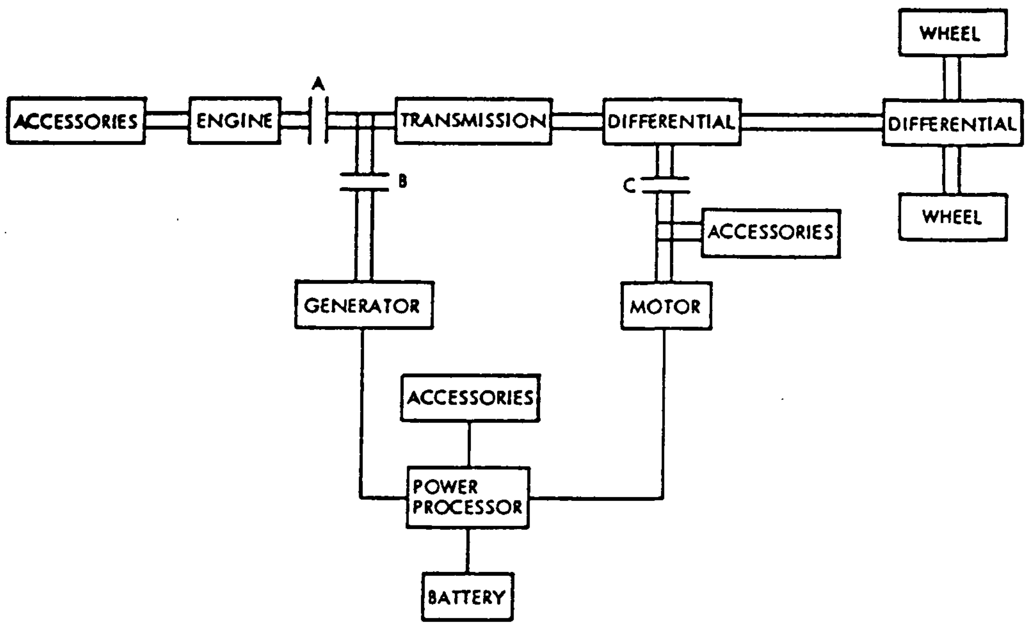


Figure 5-19. Configuration 17

Configurations 18 and 19 (Figures 5-20 and 5-21) are the same as Configurations 16 and 15, respectively, with the addition of a differential to the drivetrain. In each case, the differential can be used to "fine tune" the speed of the drivetrain (in a manner similar to a CVT) while using a transmission with relatively large gear ratio steps in a shifting gear box. The choice depends to a large extent on the characteristics of the particular transmission.

The configurations resulting from the addition of a flywheel to the electric drive with transmission configurations are shown as Configurations 20 to 25. There is a problem in the location of the flywheel which is between

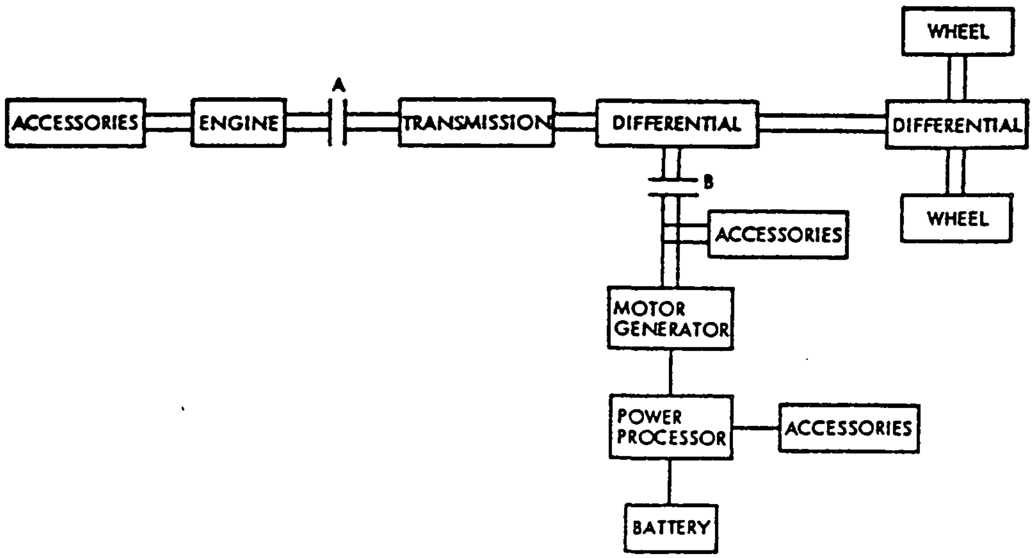


Figure 5-20. Configuration 18

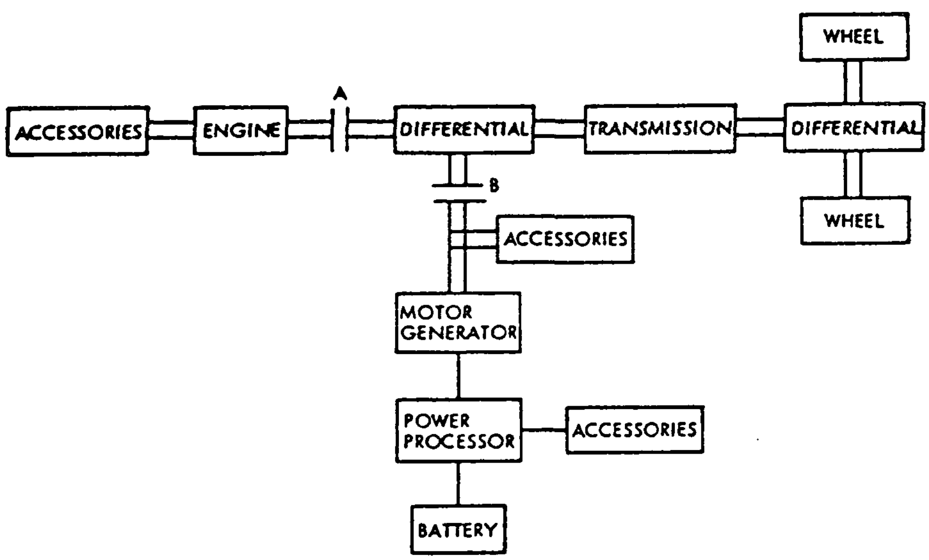


Figure 5-21. Configuration 19

the engine and transmission or between the transmission and wheels. If the flywheel is between the engine and the transmission, the engine can charge the flywheel directly, but regenerative braking power must pass through the transmission. If the flywheel is between the transmission and the wheels, the regenerative braking power can reach the flywheel directly, but power from the engine must pass through the transmission. If the flywheel and the generator are at opposite ends of the transmission, then flywheel power must pass through transmission to reach the generator. The three power paths connected to the flywheel are engine to flywheel, wheels to flywheel, and flywheel to generator. To minimize losses, because all three paths cannot be direct, two of them should be direct and one pass through the transmission. The flywheel should be directly coupled to the generator.

In Configuration 20 (Figure 5-22) the flywheel is located between the transmission and the wheels and three clutches are used. Power can be directed from the wheels to the flywheel and motor-generator without going to the output of the transmission and power can also go from the flywheel to motor-generator without going to either transmission or wheels. The flywheel can be bypassed when power is delivered by the transmission or the motor-generator to the wheels. Clutch A is optional, depending on the input characteristics of the transmission.

The flywheel in Configuration 21 (Figure 5-23) is located between the engine and the transmission where the generator is also attached. The three Clutches A, B, and C allow the power flow to and from the four components at this point for minimum losses. Clutch D allows the motor to drive the accessories on its shaft. The motor can draw its power from the battery, from the flywheel, or from the engine through the generator, as required.

Configuration 22 (Figure 5-24) is the same as Configuration 21, although one motor-generator is used instead of two separate units. Four clutches are shown, but Clutches C and D are optional; their use depends on the windage and bearing losses of the motor-generator and on the input characteristics of the transmission.

Configuration 23 (Figure 5-25) is also a variation of Configuration 21, but a differential has been added between transmission and wheels. The differential directs the power flow and allows a degree of speed control which reduces the speed range required of the transmission and the engine. The clutches serve the same functions as in Configurations 17 and 21.

Configurations 24 and 25 are basically the same with the exception of the location of the flywheel-differential-motor-generator combination. In Configuration 24 (Figure 5-26) it is located between the transmission and the wheels, whereas in Configuration 25 (Figure 5-27), it is between the engine

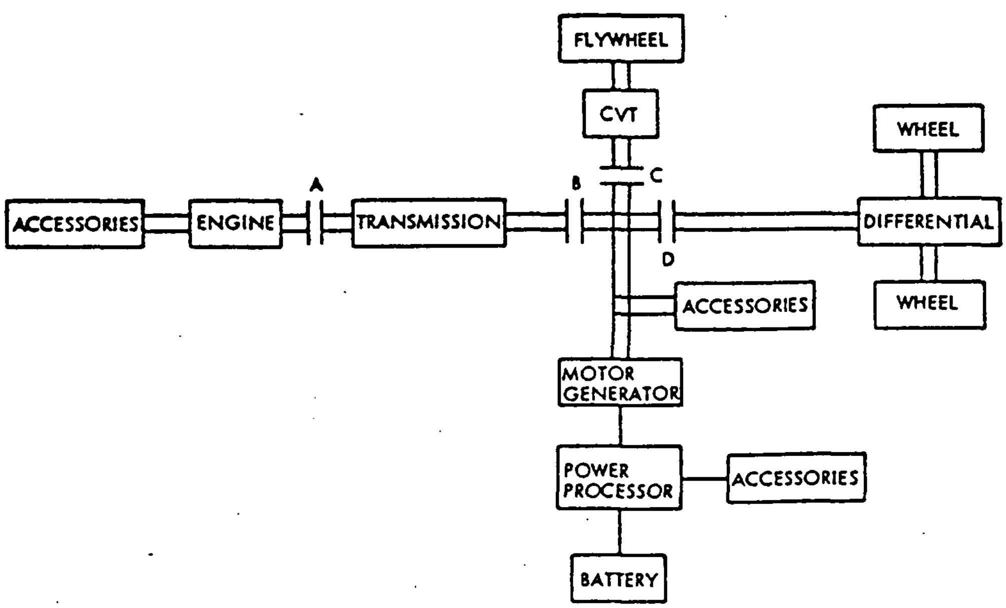


Figure 5-22. Configuration 20

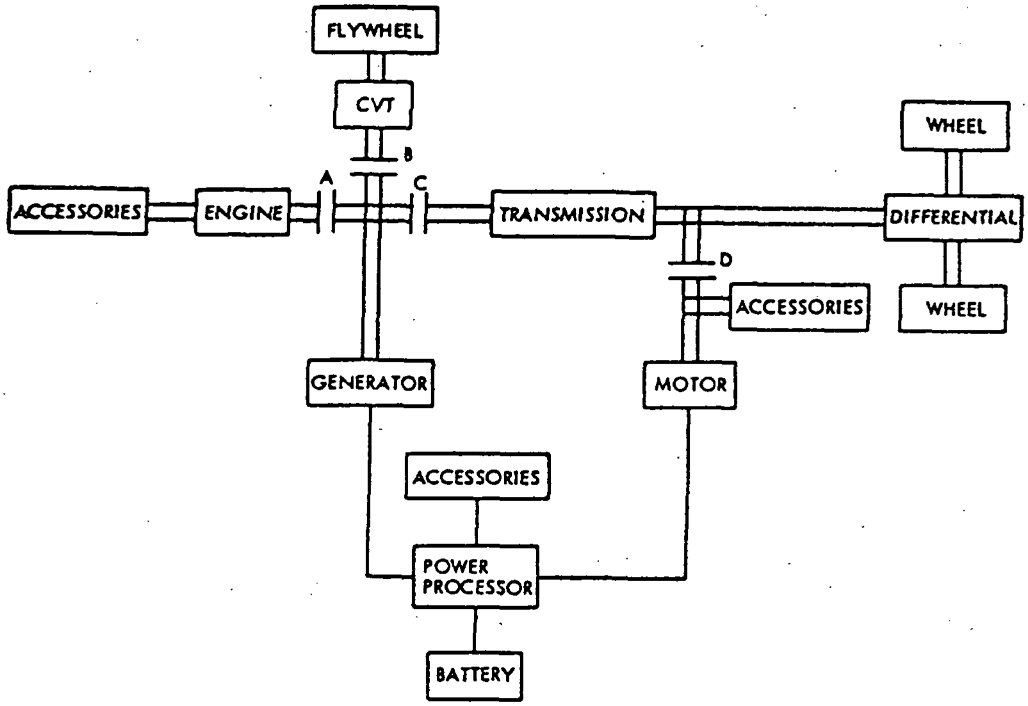


Figure 5-23. Configuration 21

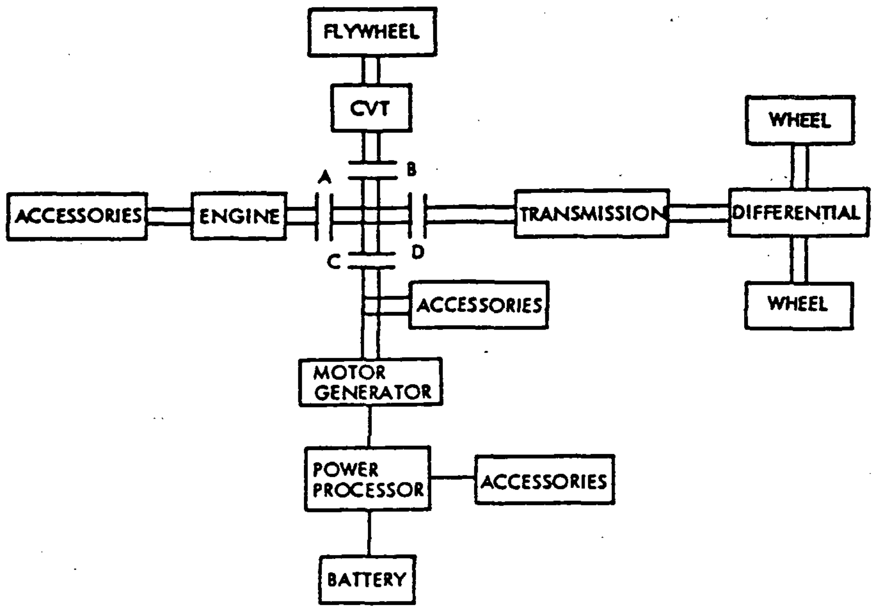


Figure 5-24. Configuration 22

and the transmission. The differential in Configuration 24 modulates the vehicle speed; in Configuration 25 it modulates the transmission input speed. All power to or from the wheels must pass through the transmission in Configuration 25, but only engine power goes through the transmission in Configuration 24.

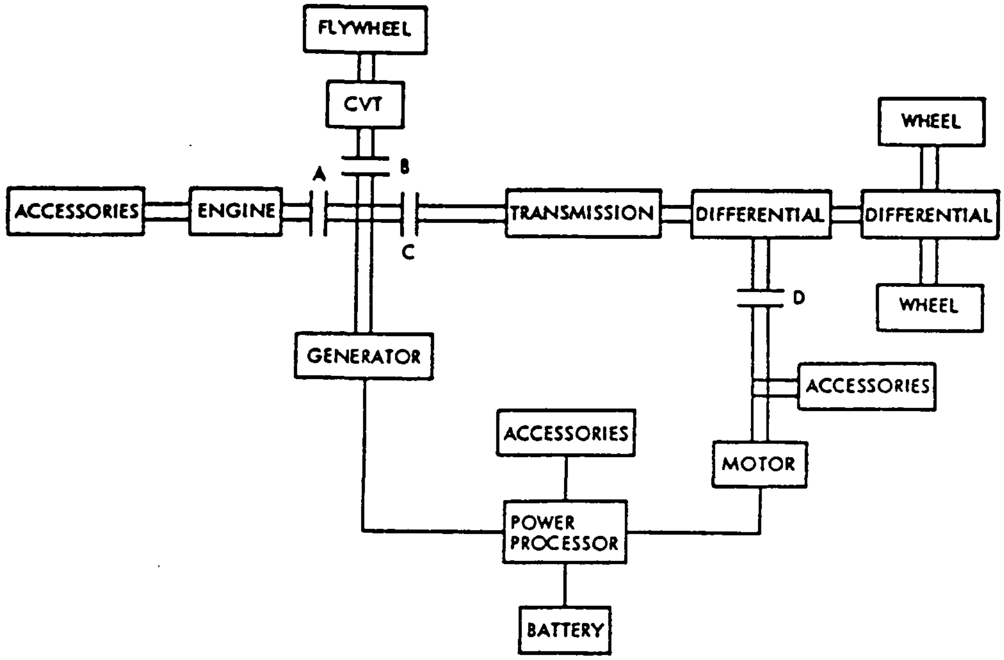


Figure 5-25. Configuration 23

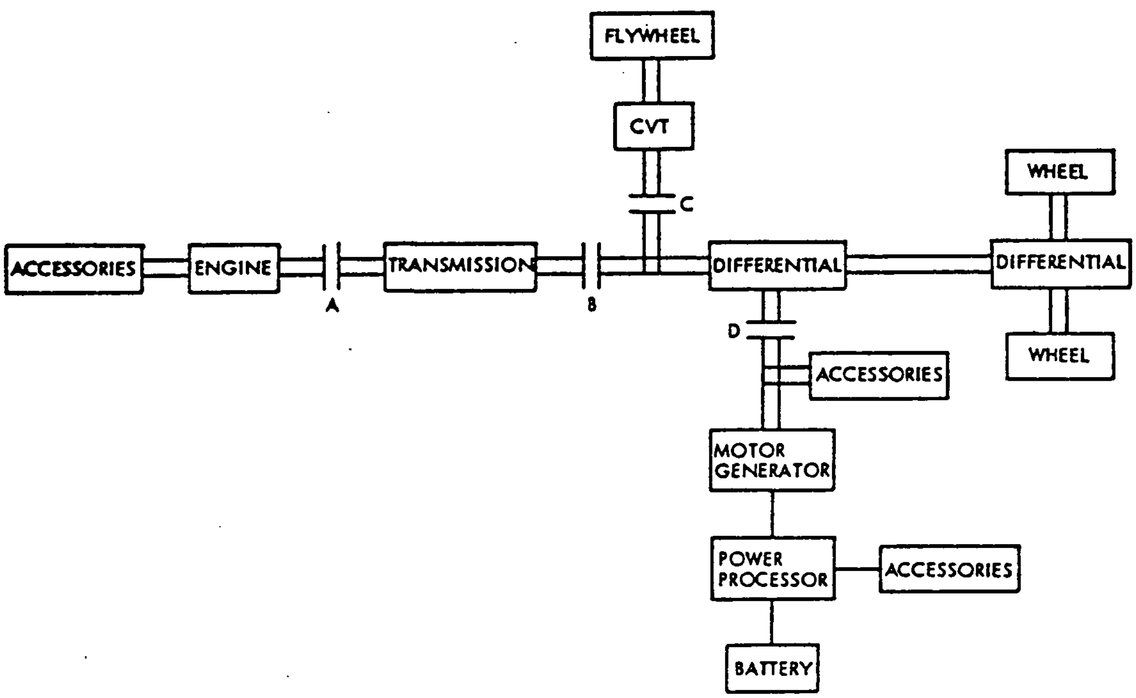


Figure 5-26. Configuration 24

All of the energy storage systems described have been connected to a single axle. The last two configurations described are split hybrids, i.e., one energy storage system drives one axle and a different system is connected to the other axle. If both energy storage systems are activated, the vehicle will have four-wheel drive. In addition, either system can be operated

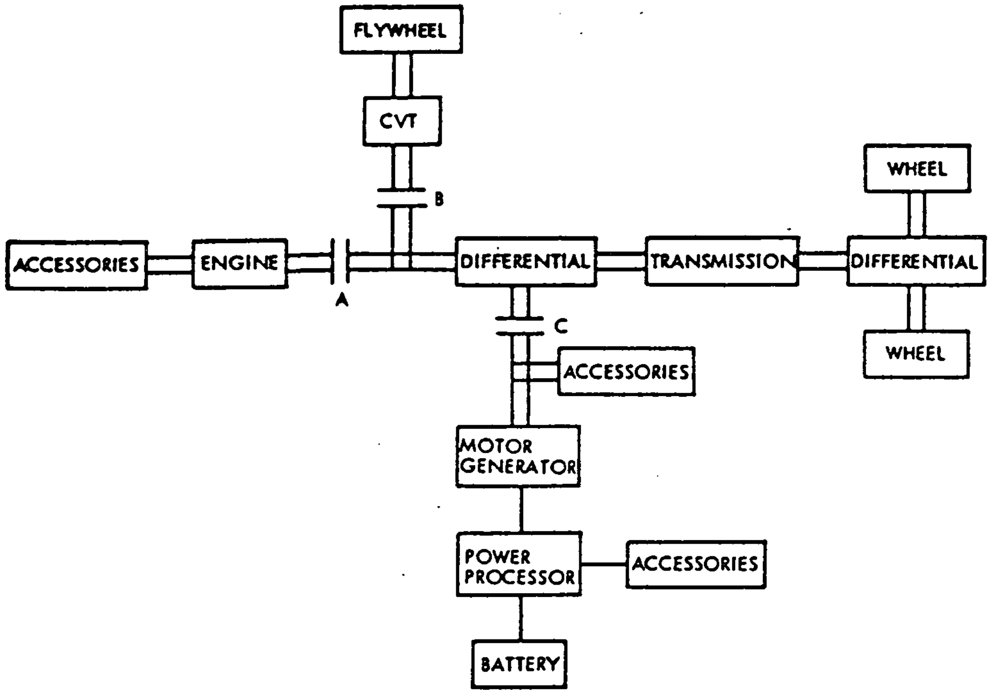


Figure 5-27. Configuration 25

independently of the other. One advantage of the split hybrids shown as Configurations 26 and 27 (Figures 5-28 and 5-29) is that part of the system (the heat engine- transmission-wheels) exists in front-wheel-drive front engine and rear-wheel- drive rear engine cars today. In Configuration 27, a third energy storage system is added, with a flywheel and CVT, to act as the electrical system buffer. One drawback to this type of hybrid is that engine power cannot be used to charge the battery or flywheel directly. In order to have the engine charge the battery, the engine must drive the car with the electrical system operating in the regenerative braking mode. This method of charging the batteries and/or flywheel (through the road and tires) is extremely inefficient. If the engine were the prime energy source for the car and the electrical system used for peak loads, these configurations could not be justified. If the electrical system is the prime energy source and the engine is used as a range extender, there are good reasons to use these configurations. When the electrical system is used for peaking, the batteries must be kept charged as much as possible to provide adequate power on demand. However, if the heat engine is used as a range extender, it does not matter if the battery is discharged during driving. The engine can get the driver home where the battery can be recharged.

The preceding description has surveyed a wide range of possible HV configurations. Although literally thousands of HV configurations are possible, these 27 were chosen for discussion and screening because there are practical limits to the wide range of weights and mechanical complexities. During the HVA these were analyzed in enough detail to ensure that their energy consumption characteristics were understood. In the next part of this section specific examples are presented. They are the most promising of the configurations studied. These were selected by a screening process in which simplified, but representative driving cycles were used to estimate the

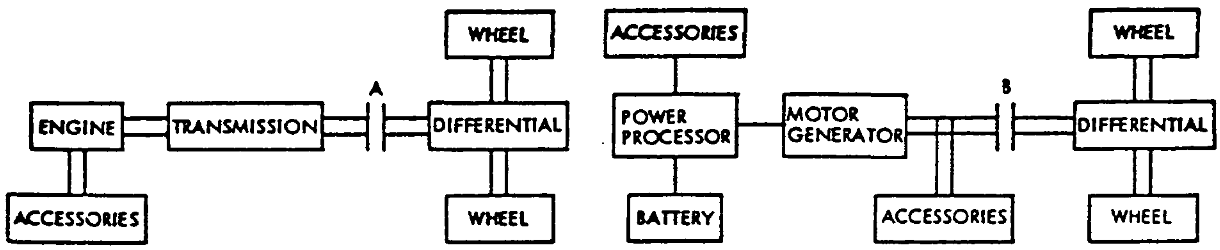


Figure 5-28. Configuration 26

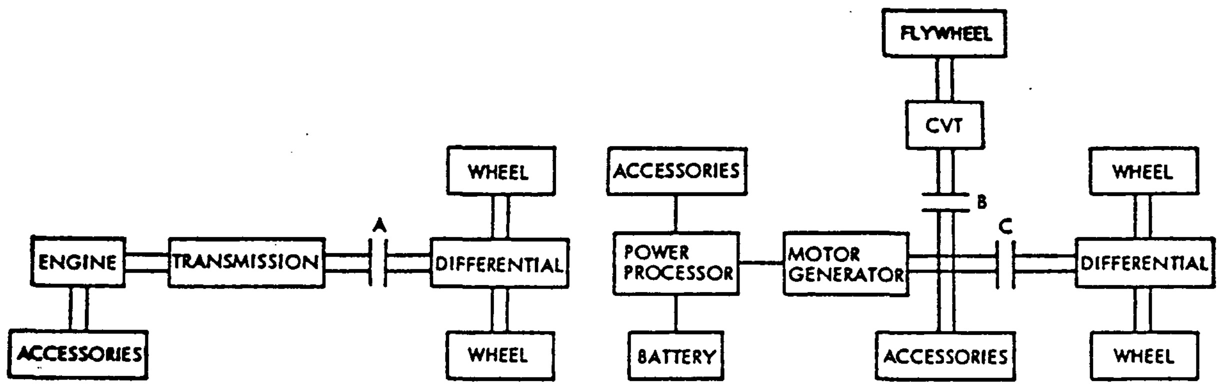


Figure 5-29. Configuration 27

petroleum consumption characteristics of each configuration. The most promising of these were then rechecked by further, more detailed simulation through the entire set of daily driving cycles for the five-passenger vehicle. The most promising HV configurations therefore received increasingly detailed analysis until optimum choices for vehicle type, configuration, energy management strategy, etc. could be selected. The flywheel configurations were analyzed for petroleum consumption and compared to the simpler two-source vehicles. Although they provide excellent power-matching characteristics, they save very little petroleum, only about 3% over annual driving patterns and do not appear to justify the additional system complexity for the five-passenger vehicle. They have therefore been relegated to comparison case status.

2. Specific Hybrids Chosen for Further Analysis

Figure 5-30 shows the traditional series configuration. Figure 5-31, shows a series/parallel configuration in which clutch action can convert the vehicle from a series hybrid to a parallel and back. When Clutch B is open, engine power reaches to the generator and the system is a series hybrid. Closing Clutch B diverts the engine power directly to the wheels. Depending on the energy management strategy, even during parallel operation, part of the engine power could reach the generator for battery recharging.

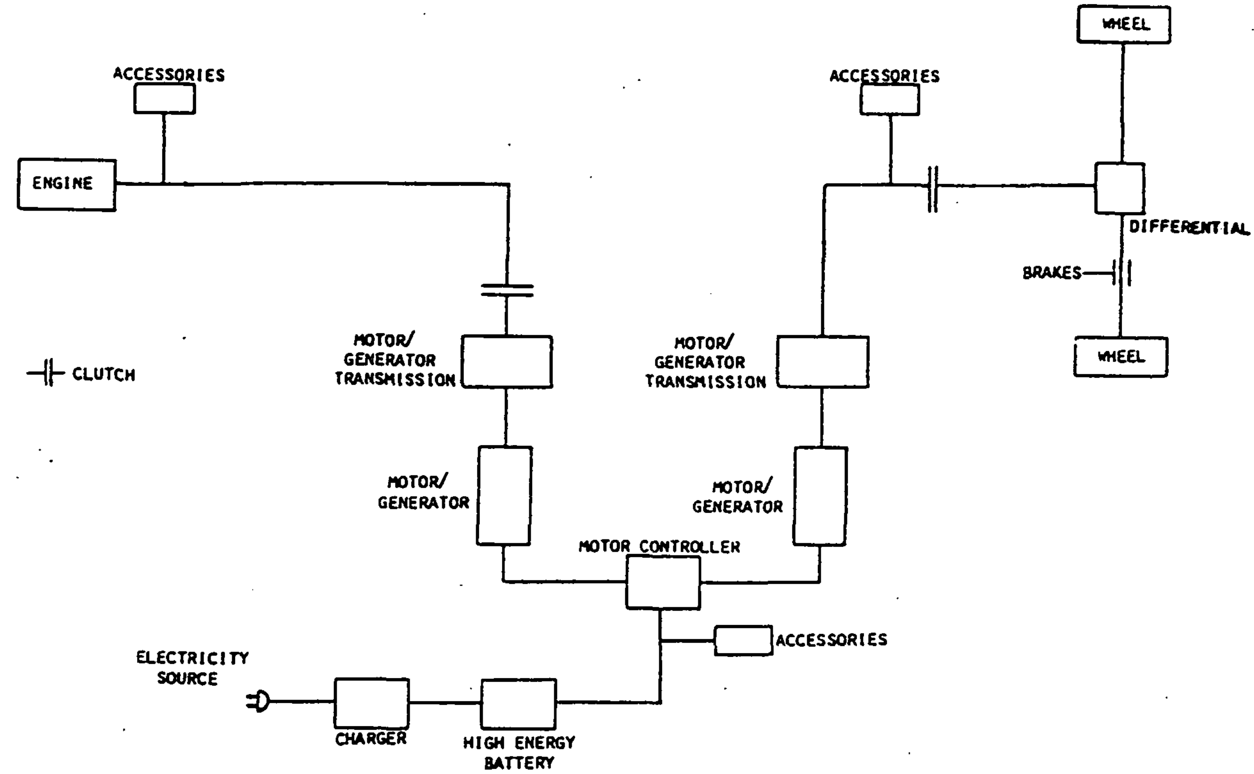


Figure 5-30. Series Hybrid Schematic

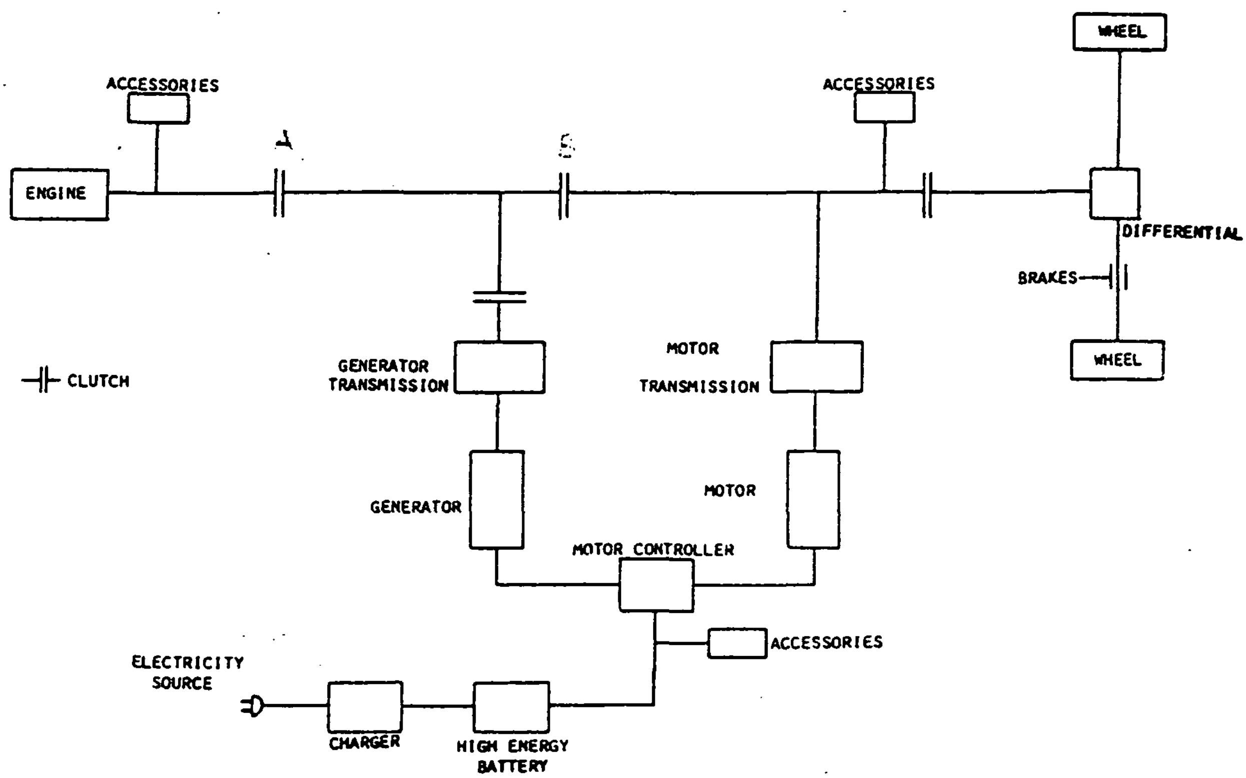


Figure 5-31. Series/Parallel Hybrid Schematic

An important discriminator for the numerous parallel configurations is the location of the motor relative to the transmission. This affects petroleum savings in several ways. If the motor is ahead of the transmission, when the car is moving slowly, the motor runs at a higher speed than if it were located behind the transmission. The motor is more efficient at the higher speed, but the losses in the transmission may cancel the efficiency gain. Having the motor behind the transmission eliminates the losses, but lowers motor efficiency at low car speeds. Therefore, two parallel configurations were chosen for further study, one with the motor ahead of the transmission (Configuration 15) and one with the motor behind the transmission (Configuration 16). Configuration 15 was then further modified to include a torque converter between engine and transmission. This configuration is shown in Figure 5-32. The rear motor parallel is shown in Figure 5-33. The arrangement used here simplifies the design of the transmission because it now serves only the engine rather than both engine and motor as in the front motor parallel (Figure 5-32). If a slipping clutch is substituted for the torque converter, then this configuration is the General Electric HTV (Figure 5-34).

A three-energy source hybrid is shown in Figure 5-35. This uses a flywheel between the motor and the wheels. As can be seen from the general diagram, this is not the only possible flywheel location. It could also be mounted ahead of the transmission.

For comparison purposes, a conventional heat engine and an electric vehicle are shown in the two following figures respectively. These two configurations can also be derived from the general diagram of Figure 5-2.

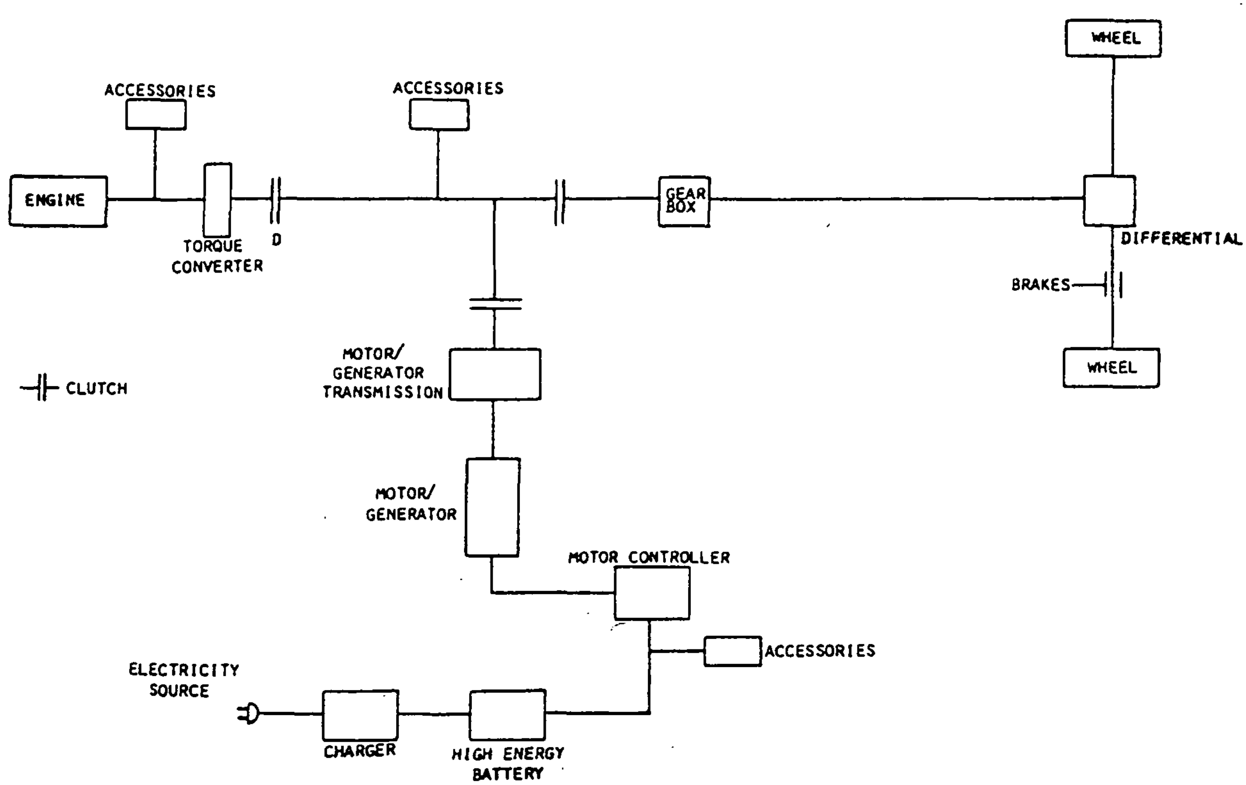


Figure 5-32. Front Motor Parallel Schematic

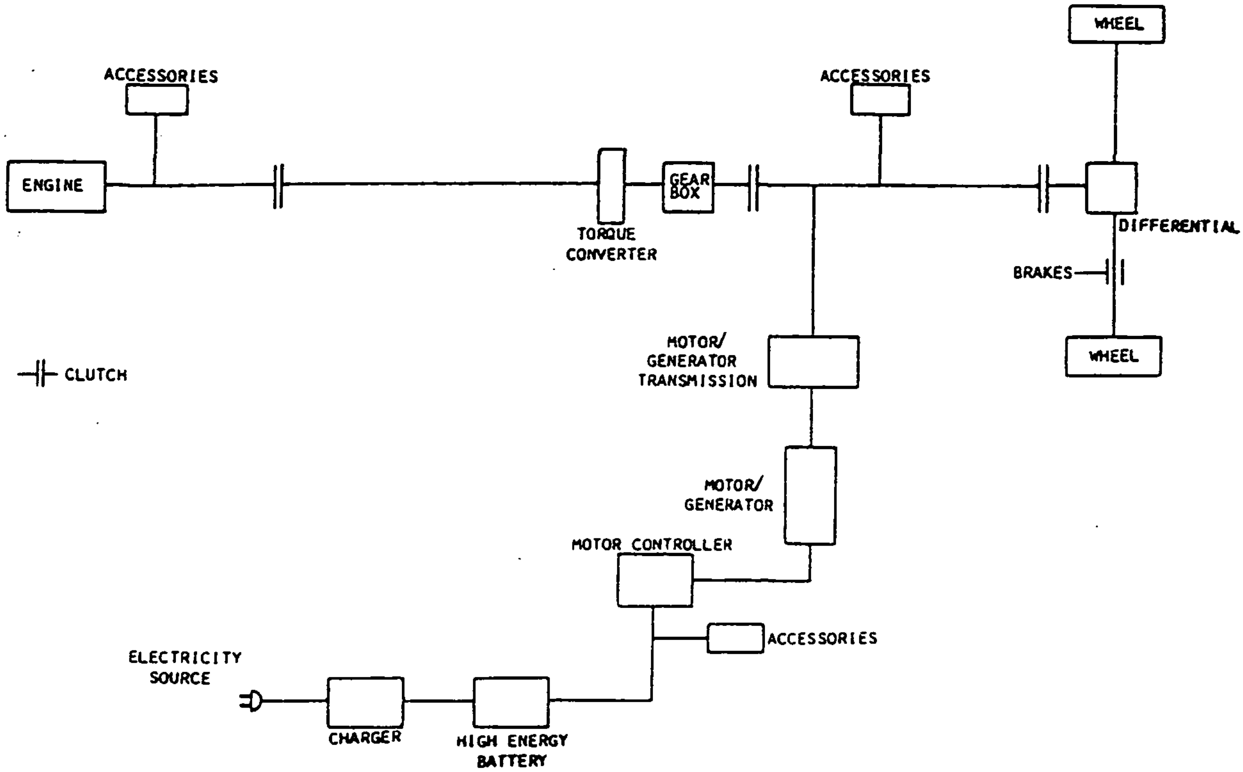


Figure 5-33. Rear Motor Parallel Schematic

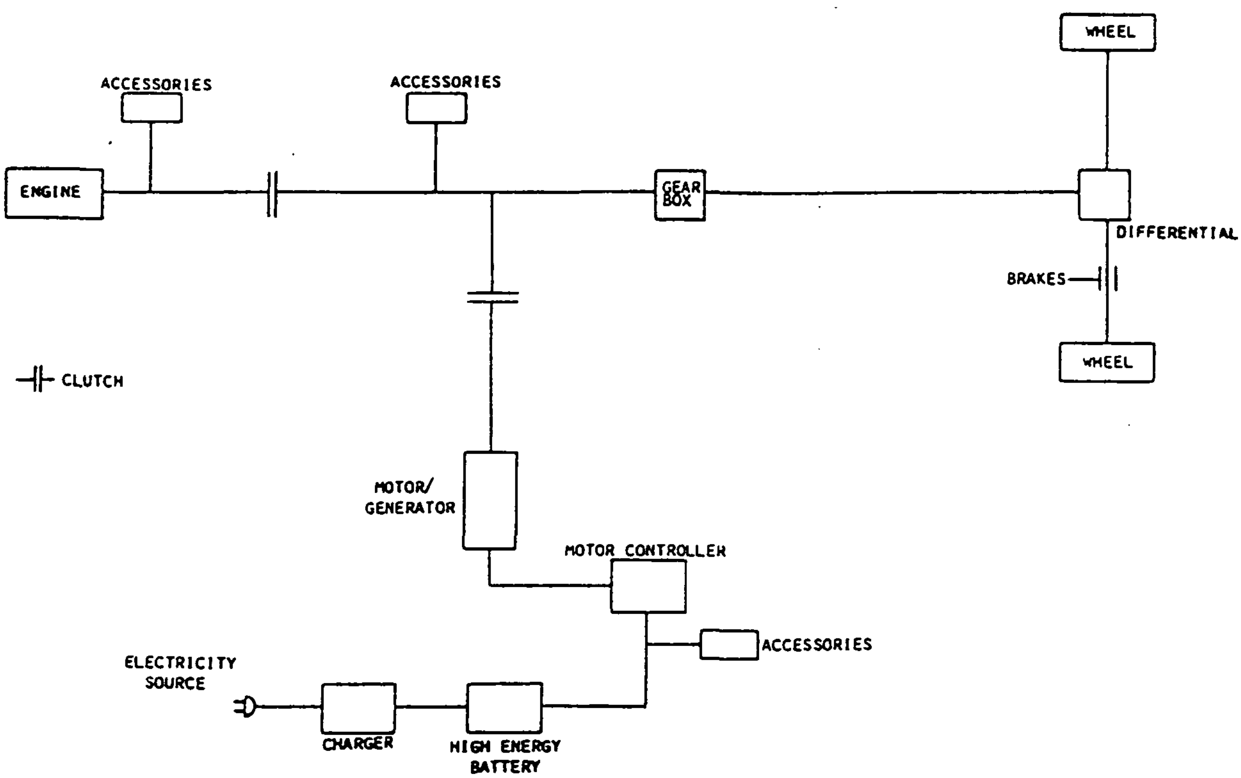


Figure 5-34. General Electric Hybrid Test Vehicle Schematic

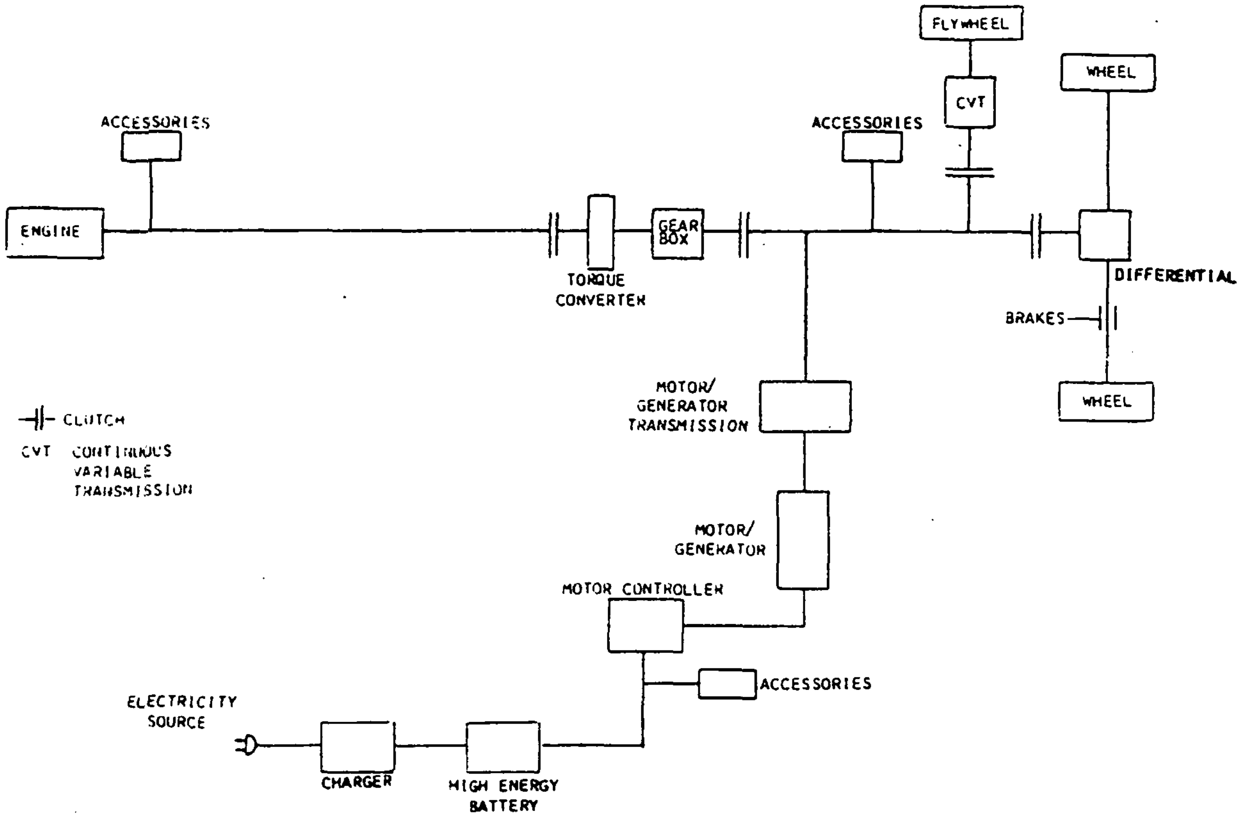


Figure 5-35. Flywheel Schematic

The power flow in these examples will be discussed in some detail as an introduction to the issue of energy management. The following discussion will explain the power paths in each configuration.

In the series hybrid shown in Figure 5-30, all road power comes from the motor which, in turn, receives its power from the motor controller. Depending on the energy management strategy, the controller gets its power from the battery, from the generator, or both. The generator is supplied by the engine.

The series/parallel shown in Figure 5-31 is somewhat different. Power going to the differential can come from either the engine directly or from the motor, depending on clutch condition. When vehicle speed is low, Clutch B is open and power flow is as described for the series hybrid. At higher speeds, Clutch B is closed and engine power goes directly to the wheels. Depending on the energy management strategy, the engine power may be used alone, or it may be supplemented by power from the motor.

The vehicle speed at which Clutch B is opened or closed depends on the power demanded from the power train. When the clutch is closed, the engine is in direct drive with the wheels. The clutch cannot be closed if the vehicle speed is so low that the engine would stall. If the clutch engagement speed is too high, much of the driving would be in the series configuration with its relatively inefficient double-energy conversion. The ideal clutch closing condition is at synchronization, i.e., when both the input shaft from the idling engine and the output shaft to the differential are running at the same speed. This condition also results in a smooth transition and long clutch life.

In the front motor parallel hybrid (Figure 5-32) all road power passes through the transmission. The input to the transmission can come from the engine, the motor, or both, depending on the energy management strategy. The motor power comes from the battery through the motor controller. The engine power comes through a torque converter before reaching the transmission. In this configuration, the transmission must handle both the engine power and the motor power. Since these two devices have markedly different characteristics, gear ratios and shift points are compromised. This system does, however, have the advantage of allowing the motor to run at higher speeds than if it were directly coupled to the wheels. The average efficiency of the motor over a normal duty cycle is, therefore, higher than for a directly coupled motor.

In the rear motor parallel (Figure 5-33), the motor is directly coupled to the differential. This arrangement allows the transmission to be matched to the engine for optimum performance. It also eliminates the transmission losses incurred in front motor parallel when the motor is used. The motor efficiency may be reduced because of the lower average motor speed, and this may partially offset the resulting gain. The power paths are from engine through transmission to differential and from the battery through the controller and motor to the differential. Depending on the energy management strategy, the two power paths can be used independently or jointly.

Another configuration shown in Figure 5-35 having the rear motor parallel with a flywheel attached and similar power flow. Power can enter amd leave the flywheel through the CVT. Flywheel power can be added to that of either the motor or the engine as required. During regenerative braking, recovered energy goes to the flywheel and any surplus goes to the battery. The flywheel can accept or yield higher levels of power than the battery. It has a much lower energy capacity, however, and is used primarily as a power buffer.

Figures 5-36 and 5-37 show the heat-engine-only and the electric vehicle power trains schematically. The power flow in each of these configurations is obvious.

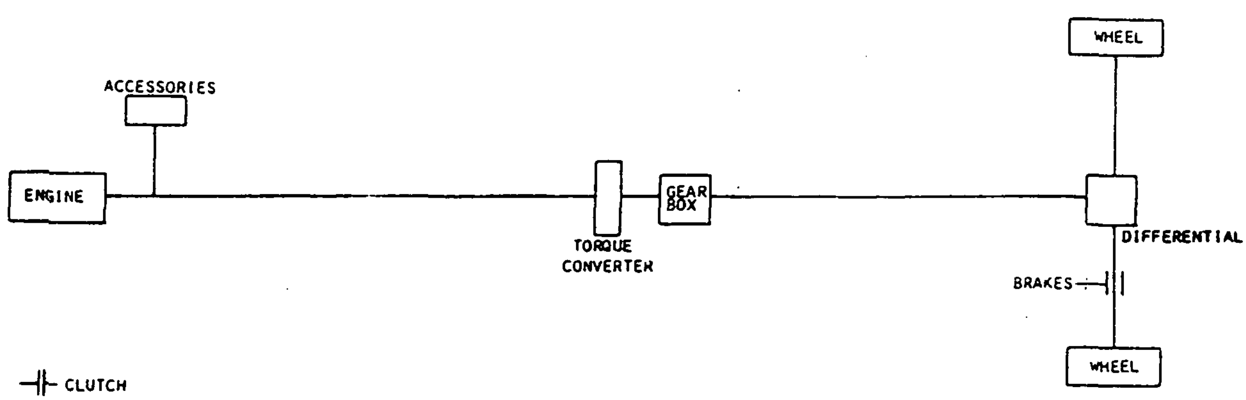


Figure 5-36. Conventional Heat Engine Schematic

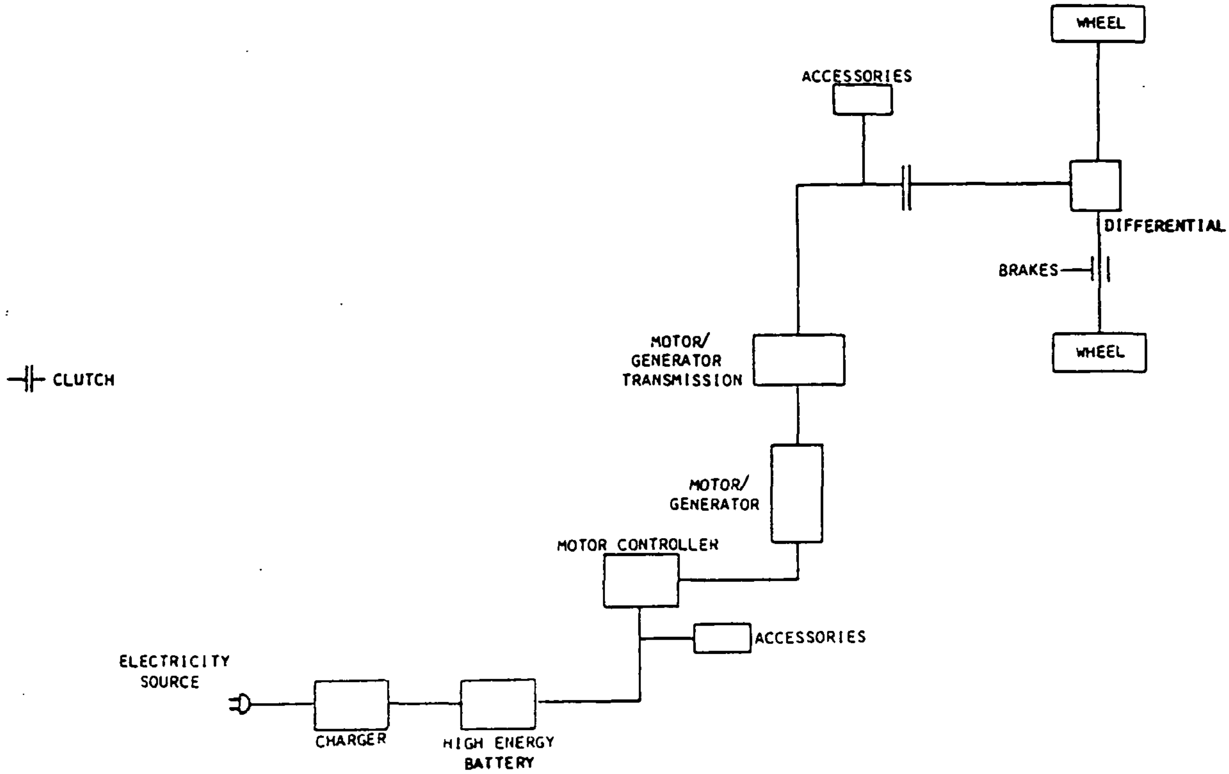


Figure 5-37. Electric Schematic

One of the vehicles used in this study for comparison is the HTV built by General Electric, shown schematically in Figure 5-34. It is identical to the front motor parallel, except that the torque converter has been replaced with a clutch. The power flow has been described. These configurations are tabulated in Table 5-1.

C. ENERGY MANAGEMENT

1. Basic Philosophy

Not only are there numerous hybrid vehicle configurations, there are many energy management strategies. The primary differences between energy management strategies involve the conditions for apportioning power demand between the available energy sources. At one extreme, each energy source is used independently; at the other extreme, all sources provide power all the time. In addition, the energy management strategy may change with time and with other criteria, i.e., battery state of charge, fuel supply, etc. Other factors involving energy management strategies may include the requirements for a limp-home capability and independence. Independence refers to the effect of the battery SOC on vehicle performance. Full independence means that the driver need not be aware of which energy source is being used. The car performs in exactly the same way all the time. Without independence, the driver must know the energy source in use and anticipate the limitations it can impose. For the average driver, full independence is required for safe operation. This concept was also introduced in Section IV.

Table 5-1. Comparison of Hybrid Vehicle Configurations

Components	Configuration: Series	Series/Parallel	Parallel	Split
Basic	1	2,5[a]	4[a]	
Differential		6	3	
Transmission		14	15,16	26[a]
Flywheel	7,8	9,12[a]	11[a]	
Differential plus transmission		17	18,19	
Differential plus flywheel		13	10	
Differential plus transmission plus flywheel		23	24,25	
Flywheel plus transmission		21	20,22	27[a]

Type of Hybrid	Configuration No.	Figure No.
Series	1	5-3
Series/parallel	2	5-4
Front motor parallel	15	5-5
Rear motor parallel	16	5-6
General Electric	15	5-7
Flywheel hybrid	20	5-8
Conventional heat engine		5-9
Electric vehicle		5-10

[a]Uses in-line motor/generator.

In series power train systems, there is no direct mechanical coupling between engine and drive wheels, and all power must be delivered by the electric motor. The motor must be sized to provide peak power requirements for maximum-effort maneuvers and be rated to avoid overheating on long sustained grades. The battery system, however, need not be sized to meet the extreme requirements of maximum-effort maneuvers or the sustained load on even short grades. In such cases, the system must rely on supplemental power from a mechanically separate generater/alternator system. Engine starting, load control, and generator/alternator control are functions that must be provided by the energy management system.

The energy management system also accomplishes similar functions in the parallel hybrids. In these configurations there is a direct mechanical path between the engine and drive wheels whenever when the engine is operating. As a result, the electric motor may be downsized to provide full vehicle performance only in the low-speed range (where peak power requirements are relatively modest), or to sustain a short-grade climb before overheating. The battery system may also be downsized to provide the full performance required in the high-speed range or the stored energy necessary for an extended grade climb. Therefore, the engine can supply supplemental power for vehicle maximum performance requirements and can supply additional energy for sustained hill climbing and range extension. The engine is normally declutched from the power train when it is not needed for supplemental power, and engine start-up may be accomplished simply by clutching the engine to the electric motor once the motor has reached engine engagement speed. The energy management system provides motor control when the engine is declutched and controls the motor and engine together for combined operation and battery charging.

The systems described above rely on "peaking" operation, e.g., the engine is called upon to overcome any power deficiencies of the motor-battery electric traction system. The engine must deliver power quickly for periods as short as one or two seconds, or for extended periods of time. Depending on the control schedule designed into the energy management system, the engine may operate under light or heavy loading.

An alternate design philosophy for the hybrid vehicle power train employs the concept of either/or. In this strategy, the motor and battery are sized to meet the maximum effort performance requirements without supplemental engine power. The engine is used only to provide extended range operation to this otherwise all-electric vehicle power train and to off-load the motor during extended grade climb operation when the motor would otherwise overheat (parallel configurations). In series range extender operations, the motor must still be rated for extended hill-climb operation because all power must pass through the motor. Since the engine is not called upon to supplement the system power, instantaneous start-up response is not required and only a short warm-up period is necessary for full power delivery and emission system stabilization. Power blending for this type of power train is limited to engine-motor load sharing.

The designer is faced with a fundamental conflict in optimizing the energy management strategy for a hybrid vehicle. Since it is desirable that maximum use be made of electric energy to achieve the greatest displacement of

petroleum, simple logic suggests that the engine should provide the minumum power necessary, and that the motor-battery provide its maximum capability at all times when the demand exceeds the motor power available.[6] However, to follow this strategy means that the engine will operate in a light load region on occasions when the driver demand barely exceeds the electrical system capability. At light loads the engine brake specific fuel consumption is poor, and the fuel is used inefficiently. On the other hand, if the engine is commanded to assume the greater share of the load under these occasions, more fuel will be consumed, even though it is used more efficiently. The resolution of this dilemma is likely to favor use of the engine in the light load region at a sacrifice in efficiency in order to minimize overall petroleum consumption.

The concept of the range extender hybrid is based on the use of battery power exclusively for all propulsion loads until its charge state is depleted to a minimum acceptable level. After that, the engine is started to maintain the battery above the minimum state and to supply the average road load. If regenerative braking energy is available, an optimized strategy calls for this energy to assist in charging the battery after battery-assisted acceleration maneuvers. The battery never falls below a minimum specified state of charge. This strategy not only provides extended driving range and fast refuelling capability but, more importantly, protects the battery from excessive discharge and the attendant life-cycle degradation. Even at the minimum charge state, the battery-motor system can provide substantial load leveling for the heat engine, thus allowing the heat engine to be downsized so it needs only to provide the average road power plus moderate battery charging power.

Once the battery has been discharged to the minimum acceptable state during all-electric operation, the question arises as to what extent and at what rate it should be recharged by the engine, if at all. The GE-HTV strategy allows discharge to the 20% state at which time the engine will recharge to the 30% level with a maximum recharge rate of 13 kW. This strategy assumes that it is undesirable to recharge more than is absolutely necessary since engine recharging consumes fuel inefficiently. The consequence of the strategy is that the engine will cycle on and off approximately once for each mile of travel for recharge purposes, in addition to the frequent cycling necessary to provide peaking power for normal urban driving. Vehicle occupants may find the frequent cycling objectionable, although it is likely that the engine will operate almost constantly under these conditions since the heavily depleted lead-acid battery can supply little of the urban driving loads.

For range extender systems or peaking systems designed with a heavier battery pack, an adaptive charging strategy might be considered. Once the battery has been discharged to the 20% level, the engine recharges it to 35%. At the time of engine shut-off, the restart SOC logic and shut-off logic levels are advanced by 5% to 25% and 40%, respectively. This ratcheting process continues until the restart and shut-off logic levels reach 35% and

---

[6]This strategy is not necessary for all batteries; for some it may be counter-productive. Nickel-iron batteries perform better when totally discharged. Flow batteries require total discharges at periodic intervals.

the engine control logic is reset to the 20/35% band[7] once the ignition switch is turned off or, alternatively, the battery is externally recharged. This adaptive logic yields the greatest petroleum savings for short urban trips, and it ensures full performance will be obtained during extended urban or highway driving. Specifically, it will provide better assurance that adequate battery energy will be available for extended grade climbs in highway driving. The penalty associated with this mode of control is that the vehicle may arrive at its destination on occasions with more than the minimum battery charge, the excess having been supplied by on-the-road engine charging. These occasions are expected to be rare for hybrids used primarily for urban driving.

The use of essentially redundant power train systems, which is key to the concept of a HV, also presents the possibility of the driver's interacting with the vehicle control logic to further optimize fuel economy, adjust performance, and accommodate to trip restrictions or driving conditions. In addition, the potential exists for providing a "limp-home" capability in the event of a failure in either the heat engine or battery-motor drive paths (an added feature not available in a conventional vehicle) which could further justify the extra initial cost of a hybrid vehicle. The most beneficial areas of driver interaction are:

(1) Vehicle performance.

(2) Trip restrictions.

(3) Terrain conditions.

(4) Trip length.

(5) Limp-home control.

The actual energy management strategies used in this study were conceptual only and were did not involve driver interaction. The following discussion is included to treat those areas of driver interaction which could be of primary concern in production HV design. It is recognized that vehicle manufacturers may have a different viewpoint regarding the desirability of possible interactions. The following discussion is intended to be descriptive and no particular advocacy should be inferred.

2. Examples of Operator Interactions

a. Vehicle Performance Control Interaction. It was noted in the previous section that maximum performance can vary substantially as a function of battery SOC when the vehicle is operated in the all-electric mode. To standardize performance, power limiting can be utilized at high 50% SOC,

---

[7]These states of charge are typical for the lead-acid battery. States of charge for other batteries will be different.

respectively, after which no further upward adjustments are made. However, road or driving conditions may occur when the driver would like to call upon the full performance available at higher SOCs for a high-speed pass, a freeway merge, or an extreme grade climb. An instrument-panel-mounted switch would allow the driver to override the power limit system for short bursts of power. This feature would also permit the option of overriding the power-limit system on a continuing basis with the attendant penalties of reduced all-electric range and variations in maximum power performance. In addition, an extra position on the same switch could enable the driver to start the engine for even more power in critical driving situations. However, if this option is provided, the automatic control system must contain an override to prevent battery overcharging in the event that the engine is inadvertently left on for an extended period of time. The effectiveness of this option would be greater in parallel (hybrids in which engine power adds directly to drive shaft power) than in series hybrids (in which engine-alternator/generator power sustains the battery voltage and all driveshaft power must be provided by the traction motor).

b. Trip Restriction Control Interaction. There is an increasing trend to restrict motor vehicle traffic in concentrated urban areas (principally in cities overseas), either for reasons of traffic congestion or air pollution. Foreign car manufacturers feel that the solution to this problem is to produce simple HVs which have small, relatively inexpensive, low-performing electric drive systems that operate almost independently of the higher-performance conventional power train. An alternative concept would integrate the electric and heat engine systems by operating exclusively on battery power below a speed of 25-30 km/h and on heat engine power above the transition vehicle speed. It would appear that a full-performance HV could be designed which would offer substantial petroleum displacement as an added bonus to the capability of operating either in the all-electric, combined, or all-heat engine modes. Regardless of the approach taken, driver interaction control may constrain the vehicle to operate in one mode or another as a result of local restrictions. This capability could be accommodated by adding a fourth position to the driver control switch described earlier. This position would inhibit engine operation, thereby forcing the system to operate in the all-electric mode.

An alternate method of driver interactive control which is applicable to full-performance range extender hybrids would provide driver control of the engine-battery charging function through an instrument-panel-mounted control knob. The control could provide for driver selection of the SOC at which engine-battery charging begins over a range from typically 20 to 90% SOC. If the driver anticipates a need to enter a restricted zone at the end of a long trip, he could set the SOC control to the 90% position far enough in advance of arrival to ensure that the battery is engine-charged to a point adequate for driving within the controlled zone. Under ordinary conditions or when travel in a controlled zone occurs at the beginning of a trip, the SOC control could be set in the 20 to 30% range.

c. Terrain Condition Control Interaction. There are cases, particularly in long-haul driving involving an extended upgrades or downgrades, the driver, by using interactive controls, could ensure that the trip is made efficiently and without complications. In the case of a long upgrade, it could be desirable to pre-charge the battery to ensure that the full capability of the dual power-train system is available. For an extended downgrade, it could be useful to discharge the battery to permit recovery of the greatest amount of available regenerative energy. Driver-interaction controls can be of use in pre-conditioning the vehicle system in anticipation of extended grades. Anticipating an upgrade, the driver could set a selector switch to the engine-on position, or set a SOC control knob to the 90% SOC level; in preparing for a downgrade, the driver could switch to the all-electric position, or set the knob at 20% to discharge the battery.

d. Trip Length Control Interaction. The design of the GE HTV includes provisions for setting a speed at which the engine will be started apart from the battery-charge state. This device, called the VMODE control, allowed the driver to select a low speed for extended highway driving which caused the engine to be turned on as soon as the VMODE speed was exceeded and thereby limited the rate of battery discharge. In the final design of the HTV it was decided to eliminate this driver interaction function, but a control is provided in an under-the-hood location for test purposes. While GE maintains that the VMODE highway setting improves highway fuel economy, projections made by JPL show little difference between the various VMODE settings. The overall (annualized) petroleum saving in urban driving can be maximized by adjusting the VMODE for vehicle performance vs distance driven and the annual profile assumed.

In general, there appears to be little value in allowing driver control of the vehicle logic on the basis of anticipated trip length. The adaptive logic suggested earlier provides a means for the system to accommodate to short and long trips.

e. Limp-Home Control Interaction. Providing a limp-home feature for a hybrid vehicle goes beyond the simple provision of added internal logic and a driver control switch. The power train system must be completely redundant (with the exception of the final drive gear and, perhaps, the transmission), and each drive system must be capable of operation independent of the other. The GE HTV does not have limp-home capability because the engine cannot provide power below 18.2 km/h. Consequently, there is no way to start the engine or to operate at low speeds without the use of the motor-battery system. It is possible to design a hybrid vehicle with a limp-home feature, but it has been found that additional mechanical assemblies are required (a clutch and starter, in the case of the GE HTV) which add to the weight and cost of the final product. It is not clear if the value of the feature justifies its cost. In the case of the HTV development, it was decided not to include the feature because of its high cost, added weight, and critical space limitations.

Hybrid vehicle engine demands may call for short pulses or sustained delivery of light or heavy power. The engine could be left on or turned off when there is no power demand. Leaving the engine on might reduce wear, lower high-emission pulses from frequent cold starts, and provide immediate availability of full power when needed. Turning off the engine when it is not needed eliminates idle fuel consumption. The Test Bed Mule (TBM) and Hybrid Power Train Mule (HPTM) development vehicles constructed for power train testing as a part of the GE-HTV program have demonstrated that emission control can be handled and that power response is adequate when the engine is operated in the intermittent on-off mode. Other tests by Volkswagen have demonstrated that engines can be operated in the on-off mode without excessive wear, even without maintaining block temperature or oil pressure at working levels. Thus, the argument against intermittent on-off operation is that of increased idle fuel consumption vs drivetrain component wear.

One unique advantage of a hybrid relative to a conventional vehicle is the potential for recovering stopping and downhill braking energy for reuse. It has been found in electric vehicles that efficient recovery of regenerative braking energy can extend the driving range up to 20%, depending on the cycle. Therefore, it can be reasoned that regenerative braking energy recovery might improve hybrid vehicle fuel economy by a similar amount.

In certain types of motor-battery power train systems, however, additional cost and complexity can result from the inclusion of regenerative braking capability. The dc traction motor systems (both series and separately excited which are armature chopper controlled) require a boost chopper to obtain full regenerative energy recovery. This will normally increase the cost and weight of the controller by up to 50%. When field weakening is used in separately excited dc traction motor systems, no added cost or weight is involved, but regenerative braking recovery is limited to speeds above that of the base motor. Because this is normally in a region where the greatest amount of recoverable regenerative energy is available, this mode of recovery is quite acceptable. The region can be extended in systems employing battery shifting or shift transmissions (either manual or automatic) in addition to field-weakening control to an extent where nearly 90% of the available regenerative energy can be recovered. The inverters used in ac motor drive systems are bi-directional and can accommodate full-range regenerative braking with only a minor addition to control logic and small penalty in system weight or cost. CVT-controlled systems require similarly small adjustments in control logic to provide full regeneration without added weight or cost.

D. ENERGY MANAGEMENT STRATEGIES

In this study, three different strategies were used to evaluate HVs. They were chosen to represent the full range of options in energy management and are shown again schematically in Figure 5-38. At one extreme is the either/or strategy shown in this figure in which each energy source is used separately to drive the vehicle. At no time are they used simultaneously. The only decision that the control system must make is when to switch from one energy source to another. This is usually based either on power overload or energy exhaustion. However, the sizing of components in a vehicle using an either/or strategy requires that each energy source be capable of supplying

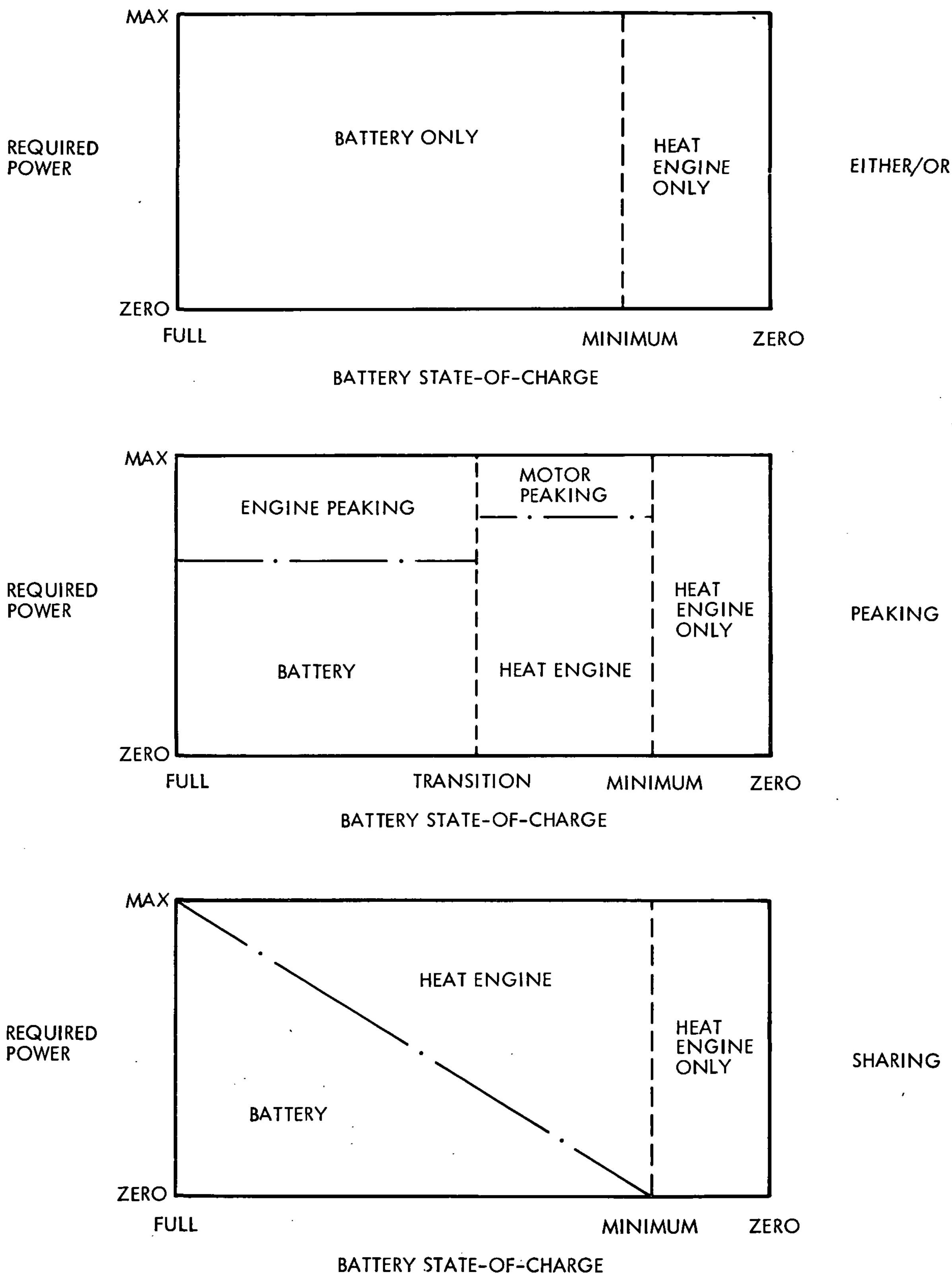


Figure 5-38. Energy Management Strategies

all required power. As a result, power overloading is not usually encountered in well-designed vehicles. When the primary energy source is the battery, the switch is made to the heat engine at the time the battery SOC reaches a specified minimum value. This depends on the type of battery, the maximum power/SOC characteristics, and battery life considerations.

At the other end of the spectrum is the sharing strategy (Figure 5-38). In the either/or strategy, each energy source was used independently. In the shared strategy, they are always used simultaneously. The role of the energy management system is to decide how to divide the power requirements between energy sources. The basis for the division may be as simple as using a fixed fraction from each energy source to using the battery SOC and maximum available power as inputs to the control system. The range of possible variations within this type of strategy is extremely wide. Within the HVA it was decided to explore one intermediate variation more complex than a fixed fraction variation but less than using two or more control system inputs. The one chosen is shown in Figure 5-38. The use of a variable fraction of power ensures full use of the battery to maximize petroleum savings.

The third strategy is peaking which is as discussed earlier and also shown schematically in Figure 5-38. This is more complex, using two battery SOCs in the control logic. When the battery is nearly at full charge, it carries the bulk of the traction load with the engine supplying peaking power. At the transition SOC, the engine assumes the base load and the battery is used for peaking service. When the battery reaches the minimum SOC, the engine assumes the entire load and the battery is not used. If regenerative braking is used, the battery never reaches the minimum SOC in normal driving, even for long distances, and the engine never has to take the full driving power load. If regenerative braking is not used, the engine can provide battery recharge as previously discussed.

E. THE HYVEC IV COMPUTER PROGRAM

Petroleum savings evaluations of the configurations and energy management strategies were made using a HYVEC IV computer program. This is an extended and modified version of the three HYVEC programs used in the Hybrid Vehicle Potential Assessment in 1979 at JPL. The original programs each simulated one particular configuration. HYVEC IV is designed to simulate the performance of 15 hybrid vehicles as well as conventional heat-engine-only and electric vehicles. This versatility allows the use of the same program to simulate all of the hybrid vehicles and the reference vehicles, thus ensuring that all results are directly comparable.

The program has a highly modular structure and consists of 220 programs, subroutines, data blocks, and run streams. It can be run in a fully interactive mode for component sizing and debugging and also in a batch mode for production runs. In addition, the vehicle can be run in a steady-speed mode, in a maximum acceleration mode, or in any one of a number of driving cycles. Combinations of driving cycles, called range cells, are also available. A more detailed description of the program appears in Appendix E. The subsystem characteristics used in the conceptual designs appear in Appendix F.

A single run is made for the daily cycles, each of which is made up of one or more range cells. For this study, 12 cycles were designed to simulate 12 different daily driving schedules. This cell representation method was found to provide sufficient detail for the analysis of 50th, 75th, and 90th percentile annual patterns if 12 or more cells were used. Increasing the number of cells improved the fidelity, but introduced additional complications in data management. The minimum of 12 cells was therefore used for all patterns. Each cycle covers a 24-hour period, considers battery self-discharge, and includes battery recharging at night. The shortest daily distance used in this study is 8 km and the longest is 560 km. By multiplying the fuel use for each of these 12 cycles (initial battery SOC considered) by the appropriate number of days per year for that mission and combining the results, the annual fuel use is computed.[8] This is accomplished using a program known as SUMMARY which also calculates the fuel and electricity use and the HV petroleum savings in comparison to the reference vehicle. Assuming that 5% of electrical power is petroleum-produced, the amount of petroleum needed to generate the required electrical energy used by the HV is calculated. A copy of a SUMMARY output page is shown in Table 5-2.

By comparing the petroleum savings from all of the configurations, energy management strategies, and vehicle types, it is possible to rank them and select those best suited to a specific application. The ELVEC program (used in the JPL Advanced Vehicle System Assessment) as presently structured is not able to accommodate the more sophisticated energy management strategies, specifically peaking and sharing. However, HYVEC IV consistency checks were made against ELVEC program predictions for a number of test vehicles using either/or strategies. For those cases in which direct comparisons were possible, consistent petroleum consumption trends and acceptable agreement were achieved.

F. COMPONENT SIZING

The term "size" usually means the peak power rating of the component (except in the case of the battery where it indicates the mass). The size of the components depends on the HV configuration, the energy management strategy, the performance criteria, and the type of vehicle. In addition to the four factors noted, the usual efficiency factors must also be considered and they, in turn, are affected by gear ratios and wheel diameters. Because there are so many factors involved in sizing, there are no simple, invariant rules for establishing component size, and each vehicle must be considered separately.

The sizes of components affect the size of the vehicle which, in turn, affects the size of other components. Hence the sizing process is repetitive, requiring several levels of iteration for convergence.

---

[8]Daily cycles and annual patterns were described in Section IV.

Table 5-2. Hybrid Vehicle Analysis - HYVEC IV

RESULTS FOR RUN NO. 2416, 90 PERCENTILE

VEHICLE- HTV CONF.- HTV STRATEGY- HTV ENGINE- SP IGN
BATTERY- NKL-ZC BATTERY MASS FRACTION- .180

DAILY SCH NO.	DAYS/ YEAR	FUEL KG/ DAY	FUEL KG/ YEAR	BATT-O KW-H/ DAY	BATT-O KW-H/ YEAR	NET BATT KW-H/ DAY	NET BATT KW-H/ YEAR
0	2	.00	.00	.00	.0	.00	.0
1	4	.22	.88	2.38	9.5	6.81	27.2
2	7	.22	1.54	3.43	24.0	7.63	53.4
3	20	.22	4.40	5.86	117.2	9.22	184.4
4	15	.43	6.45	7.84	117.6	10.74	161.1
5	63	.65	40.95	9.69	610.5	11.91	750.3
6	60	1.46	87.60	16.23	973.8	16.47	988.2
7	37	2.80	103.60	18.19	673.0	17.84	660.1
8	43	4.82	207.26	19.73	848.4	18.81	808.8
9	46	7.13	327.98	14.56	669.8	14.98	689.1
10	30	10.58	317.40	8.95	268.5	10.79	323.7
11	31	19.62	608.22	12.05	373.5	12.17	377.3
12	3	31.63	94.89	18.02	54.1	15.94	47.8
13	4	44.36	177.45	18.02	72.1	15.94	63.8
TOTALS FOR YEAR			1978.62		4812.0		5135.2

FUEL ENERGY	24218. KW-H
WALL PLUG ELECTRICAL ENERGY	5706. KW-H
ELECTRICAL SOURCE ENERGY	19557. KW-H
TOTAL VEHICLE INPUT ENERGY	29924. KW-H
TOTAL SOURCE ENERGY	43776. KW-H

FUEL EQUIV. OF ELECTRICITY(FEE)	196.81 KG/YEAR
REFERENCE VEHICLE FUEL(RVF)	1808. KG/YEAR
PETROLEUM SAVINGS PS=RVF-HFU-FEE	-367.6 KG/YEAR
	-4502. KW-H/YEAR

CURB WEIGHT 1995. KG
PS/RVF -.203
PS/CURB WEIGHT -.184

PS/TOTAL VEHICLE INPUT ENERGY	-.0123 KG/KW-H
PS/TOTAL VEHICLE INPUT ENERGY	-.1504 KW-H/KW-H
PS/TOTAL SOURCE ENERGY	-.0084 KG/KW-H
PS/TOTAL SOURCE ENERGY	-.1028 KW-H/KW-H

Finally, there may be more than one solution which meets all the criteria specified. Usually the number of variables is greater than the number of criteria, and multiple solutions are common.

In the HVA, there are three levels of sizing iteration. The first level establishes vehicle mass and component sizes to meet specified power-to-weight ratios. The size of the engine, motor, generator, transmission, motor controller, and battery are not specified directly. The peak power-to-vehicle mass ratio for each component is based upon previous data or estimates. These, as well as data on the vehicle and component mass, are iterated until a vehicle mass is established to fit all the requirements. The vehicle at this point is specified and all components are sized.

The next level of iteration determines if the vehicle can meet the performance criteria. The three categories of these are maximum speed, maximum acceleration, and gradeability are shown in Tables 5-3a and 5-3b. They were initially discussed in Section IV.

The steady-speed capabilities of the vehicle are computed on level ground and on grades. The results are then checked against the criteria and, if the criteria are met, the acceleration performances are computed and these results checked. If the criteria are not met in either of these tests, the power-to-weight ratio is modified and a new vehicle mass and component sizes are calculated. This process is repeated until the vehicle meets steady-speed, acceleration, and gradeability criteria.

Table 5-3a. Minimum Speed and Acceleration Performance Requirements for Hybrid Vehicles

		Automobile Missions	Van/Truck Missions
Sustained speed			
Freeway capability, zero grade, km/h		96	90
Acceleration manuever			
Freeway entry,	0-88 km/h, s	18	22
Low-speed pass,	30-55 km/h, s	6	8
Low-speed start,	0-50 km/h, s	7	8
Four-second distance,	from stop, m	25	20

Table 5-3b. Minimum Gradeability Performance Requirements for Hybrid Vehicles

	Grade, %	Distance, km
Gradeability (all missions)		
Freeway grades, 90 km/h	5	8
Freeway ramps and city streets, 50 km/h	7	0.4
Driveway grades, 5 km/h	30	0.1

In energy-management strategies such as the either/or, the battery must provide all the power until it is disconnected. Because of battery power limitations, there is a minimum-size which will meet the power requirements of the car, even at full charge. On the other hand, the battery could be large enough to supply all power and energy requirements, and the car operates as an electric vehicle. In the extreme case, this may result in a vehicle that may be so large and heavy that it also has high total energy consumption. (This corresponds to an extreme Quadrant III situation described in Section III.)

These considerations bracket the battery size, but do not specify it. Additional criteria for utility functions are covered in Section III. They are:

(1) Petroleum savings per unit HV mass (PS/M).

(2) Petroleum savings per unit total source energy (PS/TE).

(3) Petroleum savings per unit reference vehicle fuel (PS/RVF).

Figure 5-12 shows a typical petroleum savings vs BMF curve, the final result of a single HYVEC analysis. For small BMFs, the petroleum savings are negative. At some value of BMF, the petroleum savings curve crosses the zero line into the positive savings region. As the BMF increases beyond the crossover point, there are several possible results, depending on the details of the vehicle and the battery.

In the PS/M case, the mass of the vehicle increases faster than the battery mass. The vehicle always shows a maximum PS/M, and a value of the BMF corresponding to this maximum is desired. If the curve is fairly flat in the vicinity of the maximum petroleum savings, then other considerations (such as vehicle mass) might dictate a slightly lower PS/M with a sizeable reduction in vehicle mass.

The PS/RVF curves represented generally do not show peaks similar to the PS/M case because the normalizing function (reference vehicle fuel used) is a constant. The PS/TE curves represent an intermediate case. The normalizing function (total HV energy used) increases with increasing BMF (increasing HV mass), but the rate of increase is much slower than that for HV mass. These curves show maxima, but they are generally quite broad and flat.

Tables 5-3 through 5-10 show the design point values for the eight different configurations investigated (Table 5-11). In Tables 5-3 through 5-10, the BMF for all the hybrids except the GE HTV is 20%. The GE HTV has a BMF of 18.2%. The batteries for all the hybrids and the electric vehicle are nickel-zinc. Spark-ignition engines are used in all vehicles except the electric car. These tables are presented with common battery and BMF to allow comparisons and to illustrate the effects of component sizing. The data is summarized in Table 5-12; actual optimized BMFs appear in Table 5-13.

G. PETROLEUM SAVINGS ANALYSIS

Hybrid vehicle petroleum savings are presented in three different forms in Figure 5-39. They are petroleum savings per unit of petroleum used by the reference vehicle (PS/RVF), petroleum savings per unit HV curb mass (PS/M), and petroleum savings per unit HV total source energy (PS/TE). The first form permits the ready comparison of the percent of fuel saved (or wasted). The other two offer two utility functions (and a corresponding range for optimum BMF). The rationale for these utility functions has been discussed in Section III.

The results of the petroleum savings study are shown in the following figures. Figures 5-40 through 5-45, show the results for the selected configurations for the five-passenger vehicle, all strategies, the spark ignition engine, and the nickel-zinc battery. These figures present petroleum savings as a function of BMF (the primary design variable) for the four best configurations. The results of these figures are summarized in Table 5-14 in terms of annual percentage of reduced petroleum use.

Configuration names correlate with previous configuration numbers as follows:

(1) Front motor parallel (Figure 5-5).

(2) Rear motor parallel (Figure 5-6).

(3) Series/parallel (Figure 5-4).

(4) Series (Figure 5-3).

A similar comparison for strategy is presented in Figures 5-46 and 5-47 with the summary shown in Table 5-15. Each of these Figures 5-46 and 5-47 contains two sets of curves. In Figure 5-46, results for both the series and series/parallel hybrids are shown for the either/or, peaking, and sharing strategies. In Figure 5-47, the results for the front motor parallel and the rear motor parallel are shown for the three strategies. In all cases, the nickel-zinc battery and the spark-ignition engine were chosen as the baseline configuration for comparison of results.

The peaking strategy is best in all cases for the NiZn battery. It minimizes the use of the engine (as does the either/or) and allows smaller components. Vehicle mass and total energy requirements are therefore reduced. The peaking strategy also permits the engine and motor to complement

Table 5-4. Design Point Data for the Series Hybrid

DATE OF RUN 022784	TIME OF RUN 104001		MISSION NO. 21
CONFIGURATION	SERIES	ENERGY MGMT	PEAKING
REGENERATIVE BRAKING?	YES	ENGINE ALWAYS ON?	NO
VEHICLE TYPE	FIVE PASSENGER	VEHICLE MODE	DRIVING CYCLE

VEHICLE INFORMATION

TOTAL VEHICLE MASS	1747. KG	CHASSIS MASS	763. KG
FRONTAL AREA	2.0 M**2	ROLLING RESISTANCE	.010
COEFFICIENT OF DRAG	.40	WHEEL DIAMETER	.64 M
INITIAL BATTERY CHARGE	1.00	MIN. BATTERY CHARGE	.100
HEADWIND VELOCITY	.0 M/S	GRADE	.00
BATTERY MASS FRACTION	.200	CURB MASS	1611. KG

COMPONENT INFORMATION

COMPONENT	TYPE NO.	PEAK POWER KW	MAX. SPEED RPM	MASS KG	SPECIFIC POWER KW/KG	POWER FRACTION	MOMENT OF INERTIA KG-M**2
ENGINE	11	42.4	5500.	122.	.347	.0263	.05241
MOTOR	1	34.5	4100.	92.	.375	.0214	.03298
TRANSMISSION	1	42.4	5500.	0.	*****		.00127
MOTOR TRANS.		34.5	4100.	0.	*****		.00000
GENERATOR		26.5	5500.	71.	.375	.0164	.07000
GEN. TRANS.		26.5	5500.	0.	*****		.00000
FLYWHEEL			0.	0.		.0000	.00000
FLYWHL. TRN.			0.	0.	1.500		.00127
MTR. CONTLR.		34.5		46.	.750		
BATT. CNTLR.		34.5		0.	.750		
BATTERY	35	66.0		322.	.205		
ACCESSORIES	1						

RATIOS AND EFFICIENCIES

DIFFERENTIAL	4.57	.960
MOTOR TRANS.	1.00	1.000
GEN. TRANS.	1.00	1.000

ACCESSORIES	USED?	ACCESSORIES	USED?
ENGINE FAN	YES	WATER PUMP	NO
AIR CONDITIONING	NO	ALTERNATOR	YES
POWER STEERING	NO	RADIO	YES
HEADLIGHTS	NO	HEATER BLOWER	YES

OTHER

ENGINE IDLE SPEED	900. RPM	IDLE FUEL FLOW	1.9 G/S
TORQUE CONVERTER DIA.	.33 M	T. CONV. INERTIA	.00065 KG-M**2
FLYWHL. MAX. ENERGY	.00 KW-H	FLYWHL. SP. ENERGY	.050 KW/KG
BATTERY SP. ENERGY	.060 KW/KG	INTEGRATION STEP SIZES	2.0, 120.

Table 5-5. Design Point Data for the Series/Parallel Hybrid

DATE OF RUN 022784	TIME OF RUN 104003		MISSION NO. 21
CONFIGURATION	SERIES/PARALLEL	ENERGY MGMT	PEAKING
REGENERATIVE BRAKING?	YES	ENGINE ALWAYS ON?	NO
VEHICLE TYPE	FIVE PASSENGER	VEHICLE MODE	DRIVING CYCLE

VEHICLE INFORMATION

TOTAL VEHICLE MASS	1502. KG	CHASSIS MASS	763. KG
FRONTAL AREA	2.0 M**2	ROLLING RESISTANCE	.010
COEFFICIENT OF DRAG	.40	WHEEL DIAMETER	.61 M
INITIAL BATTERY CHARGE	1.00	MIN. BATTERY CHARGE	.100
HEADWIND VELOCITY	.0 M/S	GRADE	.00
BATTERY MASS FRACTION	.200	CURB MASS	1366. KG

COMPONENT INFORMATION

COMPONENT	TYPE NO.	PEAK POWER KW	MAX. SPEED RPM	MASS KG	SPECIFIC POWER KW/KG	POWER FRACTION	MOMENT OF INERTIA KG-M**2
ENGINE	11	25.1	5500.	82.	.307	.0184	.02537
MOTOR	1	16.9	4100.	45.	.375	.0124	.03091
TRANSMISSION	1	25.1	5500.	0.	*****		.00127
MOTOR TRANS.		16.9	4100.	0.	*****		.00000
GENERATOR		15.7	5500.	42.	.375	.0115	.07000
GEN. TRANS.		15.7	5500.	0.	*****		.00000
FLYWHEEL			0.	0.		.0000	.00000
FLYWHL. TRN.			0.	0.	1.500		.00127
MTR. CONTLR.		16.9		23.	.750		
BATT. CNTLR.		16.9		0.	.750		
BATTERY	35	56.0		273.	.205		
ACCESSORIES	1						

RATIOS AND EFFICIENCIES

DIFFERENTIAL	4.57	.960
MOTOR TRANS.	1.00	1.000
GEN. TRANS.	1.00	1.000

ACCESSORIES	USED?	ACCESSORIES	USED?
ENGINE FAN	YES	WATER PUMP	NO
AIR CONDITIONING	NO	ALTERNATOR	YES
POWER STEERING	NO	RADIO	NO
HEADLIGHTS	NO	HEATER BLOWER	NO

OTHER

ENGINE IDLE SPEED	900. RPM	IDLE FUEL FLOW	1.9 G/S
TORQUE CONVERTER DIA.	.33 M	T. CONV. INERTIA	.00065 KG-M**2
FLYWHL. MAX. ENERGY	.00 KW-H	FLYWHL. SP. ENERGY	.050 KW/KG
BATTERY SP. ENERGY	.060 KW/KG	INTEGRATION STEP SIZES	2.0, 120.

Table 5-6. Design Point Data for the Front Motor Parallel Hybrid

DATE OF RUN	022784	TIME OF RUN 1[illegible]4004	MISSION NO. 21
CONFIGURATION	FRONT MOTOR PAR.	ENERGY MGMT	PEAKING
REGENERATIVE BRAKING?	YES	ENGINE ALWAYS ON?	NO
VEHICLE TYPE	FIVE PASSENGER	VEHICLE MODE	DRIVING CYCLE

VEHICLE INFORMATION

TOTAL VEHICLE MASS	1451. KG	CHASSIS MASS	763. KG
FRONTAL AREA	2.0 M**2	ROLLING RESISTANCE	.010
COEFFICIENT OF DRAG	.40	WHEEL DIAMETER	.60 M
INITIAL BATTERY CHARGE	1.00	MIN. BATTERY CHARGE	.100
HEADWIND VELOCITY	.0 M/S	GRADE	.00
BATTERY MASS FRACTION	.200	CURB MASS	1315. KG

COMPONENT INFORMATION

COMPONENT	TYPE NO.	PEAK POWER KW	MAX. SPEED RPM	MASS KG	SPECIFIC POWER KW/KG	POWER FRACTION	MOMENT OF INERTIA KG-M**2
ENGINE	11	27.6	5500.	88.	.315	.0210	.02893
MOTOR	1	13.7	5500.	36.	.375	.0104	.02297
TRANSMISSION	1	21.9	5500.	17.	1.640		.00127
MOTOR TRANS.		13.7	5500.	3.	4.400		.00000
GENERATOR		.0	5500.	0.	.375	.0000	.07000
GEN. TRANS.		.0	5500.	0.	4.400		.00000
FLYWHEEL			0.	0.		.0000	.00000
FLYWHL. TRN.			0.	0.	1.500		.00127
MTR. CONTLR.		13.7		19.	.750		
BATT. CNTLR.		13.7		0.	.750		
BATTERY	35	53.9		263.	.205		
ACCESSORIES	1						

RATIOS AND EFFICIENCIES

TRANSMISSION	RATIO	EFFICIENCY	UPSHIFT	DOWNSHIFT
FIRST GEAR	3.03	.940	730.	450.
SECOND GEAR	1.74	.960		
THIRD GEAR	1.00	.980	1475.	909.
DIFFERENTIAL	2.55	.960		
MOTOR TRANS.	1.00	1.000		
GEN. TRANS.	1.00	1.000		

ACCESSORIES	USED?	ACCESSORIES	USED?
ENGINE FAN	YES	WATER PUMP	NO
AIR CONDITIONING	NO	ALTERNATOR	YES
POWER STEERING	NO	RADIO	NO
HEADLIGHTS	NO	HEATER BLOWER	NO

OTHER

ENGINE IDLE SPEED	900. RPM	IDLE FUEL FLOW	1.9 G/S
TORQUE CONVERTER DIA.	.18 M	T. CONV. INERTIA	.00065 KG-M**2
FLYWHL. MAX. ENERGY	.00 KW-H	FLYWHL. SP. ENERGY	.050 KW/KG
BATTERY SP. ENERGY	.060 KW/KG	INTEGRATION STEP SIZES	2.0, 12.0.

Table 5-7. Design Point Data for the Rear Motor Parallel Hybrid

DATE OF RUN	022784	TIME OF RUN	104006	MISSION NO.	21
CONFIGURATION	REAR MOTOR PARA.	ENERGY MGMT	PEAKING		
REGENERATIVE BRAKING?	YES	ENGINE ALWAYS ON?	NO		
VEHICLE TYPE	FIVE PASSENGER	VEHICLE MODE	DRIVING CYCLE		

VEHICLE INFORMATION

TOTAL VEHICLE MASS	1444. KG	CHASSIS MASS	763. KG
FRONTAL AREA	2.0 M**2	ROLLING RESISTANCE	.010
COEFFICIENT OF DRAG	.40	WHEEL DIAMETER	.60 M
INITIAL BATTERY CHARGE	1.00	MIN. BATTERY CHARGE	.100
HEADWIND VELOCITY	.0 M/S	GRADE	.00
BATTERY MASS FRACTION	.200	CURB MASS	1308. KG

COMPONENT INFORMATION

COMPONENT	TYPE NO.	PEAK POWER KW	MAX. SPEED RPM	MASS KG	SPECIFIC POWER KW/KG	POWER FRACTION	MOMENT OF INERTIA KG-M**2
ENGINE	11	27.2	5500.	87.	.314	.0208	.02831
MOTOR	1	13.1	5500.	35.	.375	.0100	.02157
TRANSMISSION	1	27.2	5500.	17.	1.640		.00127
MOTOR TRANS.		13.1	5500.	3.	4.400		.00000
GENERATOR		.0	5500.	0.	.375	.0000	.07000
GEN. TRANS.		.0	5500.	0.	4.400		.00000
FLYWHEEL			0.	0.		.0000	.00000
FLYWHL. TRN.			0.	0.	1.500		.00127
MTR. CONTLR.		13.1		17.	.750		
BATT. CNTLR.		13.1		0.	.750		
BATTERY	35	53.6		262.	.205		
ACCESSORIES	1						

RATIOS AND EFFICIENCIES

TRANSMISSION	RATIO	EFFICIENCY	UPSHIFT	DOWNSHIFT
FIRST GEAR	3.39	.940	2400.	1000.
SECOND GEAR	1.84	.960		
THIRD GEAR	1.00	.980	5257.	2429.
DIFFERENTIAL	3.41	.960		
MOTOR TRANS.	1.54	.980		
GEN. TRANS.	1.00	1.000		

ACCESSORIES	USED?	ACCESSORIES	USED?
ENGINE FAN	YES	WATER PUMP	NO
AIR CONDITIONING	NO	ALTERNATOR	YES
POWER STEERING	NO	RADIO	NO
HEADLIGHTS	NO	HEATER BLOWER	NO

OTHER

ENGINE IDLE SPEED	900. RPM	IDLE FUEL FLOW	1.9 G/S
TORQUE CONVERTER DIA.	.25 M	T. CONV. INERTIA	.00065 KG-M**2
FLYWHL. MAX. ENERGY	.00 KW-H	FLYWHL. SP. ENERGY	.050 KW/KG
BATTERY SP. ENERGY	.060 KW/KG	INTEGRATION STEP SIZES	2.0, 120.

Table 5-8. Design Point Data for the General Electric Hybrid Test Vehicle

DATE OF RUN	022784	TIME OF RUN	104009
MISSION NO.	21		
CONFIGURATION	G.E. HYBRID T.V.	ENERGY MGMT	H.T.V.
REGENERATIVE BRAKING?	YES	ENGINE ALWAYS ON?	NO
VEHICLE TYPE	FOUR PASSENGER	VEHICLE MODE	DRIVING CYCLE

VEHICLE INFORMATION

TOTAL VEHICLE MASS	2090. KG	CHASSIS MASS	889. KG
FRONTAL AREA	2.1 M**2	ROLLING RESISTANCE	.011
COEFFICIENT OF DRAG	.45	WHEEL DIAMETER	.68 M
INITIAL BATTERY CHARGE	1.00	MIN. BATTERY CHARGE	.100
HEADWIND VELOCITY	.0 M/S	GRADE	.00
BATTERY MASS FRACTION	.182	CURB MASS	1955. KG

COMPONENT INFORMATION

COMPONENT	TYPE NO.	PEAK POWER KW	MAX. SPEED RPM	MASS KG	SPECIFIC POWER KW/KG	POWER FRACTION	MOMENT OF INERTIA KG-M**2
ENGINE	10	55.9	5500.	178.	.314	.0290	.07699
MOTOR	1	34.7	5500.	112.	.310	.0174	.08379
TRANSMISSION	1	55.9	5500.	119.	.471		.00127
MOTOR TRANS.		34.7	5500.	0.	*****		.00000
GENERATOR		.0	5500.	0.	*****	.0000	.07000
GEN. TRANS.		.0	5500.	0.	*****		.00000
FLYWHEEL			0.	0.		.0000	.00000
FLYWHL. TRN.			0.	0.	1.500		.00127
MTR. CONTLR.		34.7		81.	.431		
BATT. CNTLR.		34.7		0.	.750		
BATTERY	35	74.4		363.	.205		
ACCESSORIES	2						

RATIOS AND EFFICIENCIES

TRANSMISSION	RATIO	EFFICIENCY	UPSHIFT	DOWNSHIFT
FIRST GEAR	2.84	.950	1850.	1000.
SECOND GEAR	1.60	.970		
THIRD GEAR	1.00	.990	3820.	2111.
DIFFERENTIAL	2.84	.960		
MOTOR TRANS.	1.00	1.000		
GEN. TRANS.	1.00	1.000		

ACCESSORIES	USED?	ACCESSORIES	USED?
ENGINE FAN	YES	WATER PUMP	YES
AIR CONDITIONING	YES	ALTERNATOR	YES
POWER STEERING	YES	RADIO	YES
HEADLIGHTS	YES	HEATER BLOWER	YES

OTHER

ENGINE IDLE SPEED	800. RPM	IDLE FUEL FLOW	1.1 G/S
TORQUE CONVERTER DIA.	.33 M	T. CONV. INERTIA	.00065 KG-M**2
FLYWHL. MAX. ENERGY	.00 KW-H	FLYWHL. SP. ENERGY	.050 KH/KG
BATTERY SP. ENERGY	.060 KW/KG	INTEGRATION STEP SIZES	2.0, 120.

Table 5-9. Design Point Data for the Flywheel Hybrid

DATE OF RUN 022784	TIME OF RUN 104011		MISSION NO. 21
CONFIGURATION	FLYWHEEL HYBRID	ENERGY MGMT	TYPE 211
REGENERATIVE BRAKING?	YES	ENGINE ALWAYS ON?	NO
VEHICLE TYPE	FIVE PASSENGER	VEHICLE MODE	DRIVING CYCLE

VEHICLE INFORMATION

TOTAL VEHICLE MASS	1577. KG	CHASSIS MASS	763. KG
FRONTAL AREA	2.0 M**2	ROLLING RESISTANCE	.010
COEFFICIENT OF DRAG	.40	WHEEL DIAMETER	.62 M
INITIAL BATTERY CHARGE	1.00	MIN. BATTERY CHARGE	.100
HEADWIND VELOCITY	.0 M/S	GRADE	.00
BATTERY MASS FRACTION	.200	CURB MASS	1441. KG

COMPONENT INFORMATION

COMPONENT	TYPE NO.	PEAK POWER KW	MAX. SPEED RPM	MASS KG	SPECIFIC POWER KW/KG	POWER FRACTION	MOMENT OF INERTIA KG-M**2
ENGINE	11	35.4	5500.	106.	.334	.0246	.04091
MOTOR	1	20.5	5500.	55.	.375	.0142	.04018
TRANSMISSION	1	35.4	5500.	22.	1.640		.00127
MOTOR TRANS.		20.5	5500.	5.	4.400		.00000
GENERATOR		.0	5500.	0.	.375	.0000	.07000
GEN. TRANS.		.0	5500.	0.	4.400		.00000
FLYWHEEL			3600.	20.		.0000	******
FLYWHL. TRN.			3600.	0.	1.500		.00127
MTR. CONTLR.		20.5		27.	.750		
BATT. CNTLR.		20.5		0.	.750		
BATTERY	35	59.1		238.	.205		
ACCESSORIES	1						

RATIOS AND EFFICIENCIES

TRANSMISSION	RATIO	EFFICIENCY	UPSHIFT	DOWNSHIFT
FIRST GEAR	3.03	.940	2500.	1000.
SECOND GEAR	1.74	.960		
THIRD GEAR	1.00	.980	5663.	2633.
DIFFERENTIAL	3.18	.960		
MOTOR TRANS.	1.54	.980		
GEN. TRANS.	1.00	1.000		

ACCESSORIES	USED?	ACCESSORIES	USED?
ENGINE FAN	YES	WATER PUMP	NO
AIR CONDITIONING	NO	ALTERNATOR	YES
POWER STEERING	NO	RADIO	NO
HEADLIGHTS	NO	HEATER BLOWER	NO

OTHER

ENGINE IDLE SPEED	900. RPM	IDLE FUEL FLOW	1.9 G/S
TORQUE CONVERTER DIA.	.33 M	T. CONV. INERTIA	.00065 KG-M**2
FLYWHL. MAX. ENERGY	1.00 KW-H	FLYWHL. SP. ENERGY	.050 KW/KG
BATTERY SP. ENERGY	.060 KW/KG	INTEGRATION STEP SIZES	2.0, 120.

Table 5-10. Design Point Data for the Conventional Spark-Ignition Engine

DATE OF RUN	022784	TIME OF RUN	104013
MISSION NO.	21		
CONFIGURATION	HEAT ENGINE ONLY	ENERGY MGMT	HEAT ENGINE ONLY
REGENERATIVE BRAKING?	NO	ENGINE ALWAYS ON?	YES
VEHICLE TYPE	FIVE PASSENGER	VEHICLE MODE	DRIVING CYCLE

VEHICLE INFORMATION

TOTAL VEHICLE MASS	1068. KG	CHASSIS MASS	763. KG
FRONTAL AREA	2.0 M**2	ROLLING RESISTANCE	.010
COEFFICIENT OF DRAG	.40	WHEEL DIAMETER	.56 M
INITIAL BATTERY CHARGE	1.00	MIN. BATTERY CHARGE	.400
HEADWIND VELOCITY	.0 M/S	GRADE	.00
BATTERY MASS FRACTION	.000	CURB MASS	932. KG

COMPONENT INFORMATION

COMPONENT	TYPE NO.	PEAK POWER KW	MAX. SPEED RPM	MASS KG	SPECIFIC POWER KW/KG	POWER FRACTION	MOMENT OF INERTIA KG-M**2
ENGINE	11	36.3	5500.	108.	.336	.0390	.04235
MOTOR	1	.0	5500.	0.	.375	.0000	.07000
TRANSMISSION	1	36.3	5500.	22.	1.640		.00127
MOTOR TRANS.		.0	5500.	0.	*****		.00000
GENERATOR		.0	5500.	0.	.375	.0000	.07000
GEN. TRANS.		.0	5500.	0.	*****		.00000
FLYWHEEL			0.	0.		.0000	.00000
FLYWHL. TRN.			0.	0.	1.500		.00127
MTR. CONTLR.		.0		0.	.750		
BATT. CNTLR.		.0		0.	.750		
BATTERY	37	.0		0.	.180		
ACCESSORIES	2						

RATIOS AND EFFICIENCIES

TRANSMISSION	RATIO	EFFICIENCY	UPSHIFT	DOWNSHIFT
FIRST GEAR	3.27	.940	2500.	1000.
SECOND GEAR	1.80	.960		
THIRD GEAR	1.00	.980	5663.	2633.
DIFFERENTIAL	3.37	.960		
MOTOR TRANS.	1.00	1.000		
GEN. TRANS.	1.00	1.000		

ACCESSORIES	USED?	ACCESSORIES	USED?
ENGINE FAN	YES	WATER PUMP	NO
AIR CONDITIONING	NO	ALTERNATOR	YES
POWER STEERING	NO	RADIO	NO
HEADLIGHTS	NO	HEATER BLOWER	NO

OTHER

ENGINE IDLE SPEED	900. RPM	IDLE FUEL FLOW	1.9 G/S
TORQUE CONVERTER DIA.	.33 M	T. CONV. INERTIA	.00065 KG-M**2
FLYWHL. MAX. ENERGY	.00 KW-H	FLYWHL. SP. ENERGY	.050 KW/KG
BATTERY SP. ENERGY	.046 KW/KG	INTEGRATION STEP SIZES	2.0, 120.

Table 5-11. Design Point Data for the Electric Vehicle

DATE OF RUN	022784	TIME OF RUN	104016
MISSION NO. 21			
CONFIGURATION	ELECTRIC VEHICLE	ENERGY MGMT	ALL ELECTRIC
REGENERATIVE BRAKING?	YES	ENGINE ALWAYS ON?	NO
VEHICLE TYPE	FIVE PASSENGER	VEHICLE MODE	DRIVING CYCLE

VEHICLE INFORMATION

TOTAL VEHICLE MASS	1374. KG	CHASSIS MASS	763. KG
FRONTAL AREA	2.0 M**2	ROLLING RESISTANCE	.010
COEFFICIENT OF DRAG	.40	WHEEL DIAMETER	.60 M
INITIAL BATTERY CHARGE	1.00	MIN. BATTERY CHARGE	.100
HEADWIND VELOCITY	.0 M/S	GRADE	.00
BATTERY MASS FRACTION	.200	CURB MASS	1238. KG

COMPONENT INFORMATION

COMPONENT	TYPE NO.	PEAK POWER KW	MAX. SPEED RPM	MASS KG	SPECIFIC POWER KW/KG	POWER FRACTION	MOMENT OF INERTIA KG-M**2
ENGINE	10	.0	5500.	0.	.000	.0000	.07000
MOTOR	1	28.0	5500.	75.	.375	.0226	.06205
TRANSMISSION	1	.0	5500.	0.	1.640		.00127
MOTOR TRANS.		28.0	5500.	6.	4.400		.00000
GENERATOR		.0	5500.	0.	.375	.0000	.07000
GEN. TRANS.		.0	5500.	0.	4.400		.00000
FLYWHEEL			0.	0.		.0000	.00000
FLYWHL. TRN.			0.	0.	1.500		.00127
MTR. CONTLR.		28.0		37.	.750		
BATT. CNTLR.		28.0		0.	.750		
BATTERY	35	50.7		248.	.205		
ACCESSORIES	2						

RATIOS AND EFFICIENCIES

TRANSMISSION	RATIO	EFFICIENCY	UPSHIFT	DOWNSHIFT
FIRST GEAR	3.03	.884	1800.	1000.
SECOND GEAR	1.74	.893		
THIRD GEAR	1.00	.902	4793.	3106.
DIFFERENTIAL	3.18	.960		
MOTOR TRANS.	1.54	.980		
GEN. TRANS.	1.00	1.000		

ACCESSORIES	USED?	ACCESSORIES	USED?
ENGINE FAN	NO	WATER PUMP	NO
AIR CONDITIONING	NO	ALTERNATOR	NO
POWER STEERING	NO	RADIO	NO
HEADLIGHTS	NO	HEATER BLOWER	NO

OTHER

ENGINE IDLE SPEED	900. RPM	IDLE FUEL FLOW	1.1 G/S
TORQUE CONVERTER DIA.	.33 M	T. CONV. INERTIA	.00065 KG-M**2
FLYWHL. MAX. ENERGY	.00 KW-H	FLYWHL. SP. ENERGY	.050 KW/KG
BATTERY SP. ENERGY	.060 KW/KG	INTEGRATION STEP SIZES	2.0, 120.

Table 5-12. Design Point Values for Tables 5-3 Through 5-10

Table	Configuration	Configuration No.	Figure
5-4	Series	1	5-30
5-5	Series/parallel	2	5-31
5-6	Front motor parallel	15	5-32
5-7	Rear motor parallel	16	5-33
5-8	GE Hybrid Test Vehicle	15	5-34
5-9	Flywheel hybrid	20	5-35
5-10	Conventional spark-ignition engine	--	5-36
5-11	Electric vehicle	--	5-37

Table 5-13. Peak Petroleum Savings for Various Batteries

Battery	Peak Petroleum Savings	Battery Optimum Mass Fraction
Aluminum-Air	0.93[a]	0.13
Sodium-Sulfur	0.76	0.21
Lithium Aluminum - iron disulfide	0.76	0.21
Lithium Aluminum - iron sulfide	0.69	0.22
Nikel-Zinc	0.65	0.25
Nickel-Iron	0.57	0.27
Zinc-Chlorine	0.56	0.32
Lead-Acid	0.40	0.23

[a]0.93 represents a 93% reduction in annual petroleum usage as compared to a conventional vehicle.

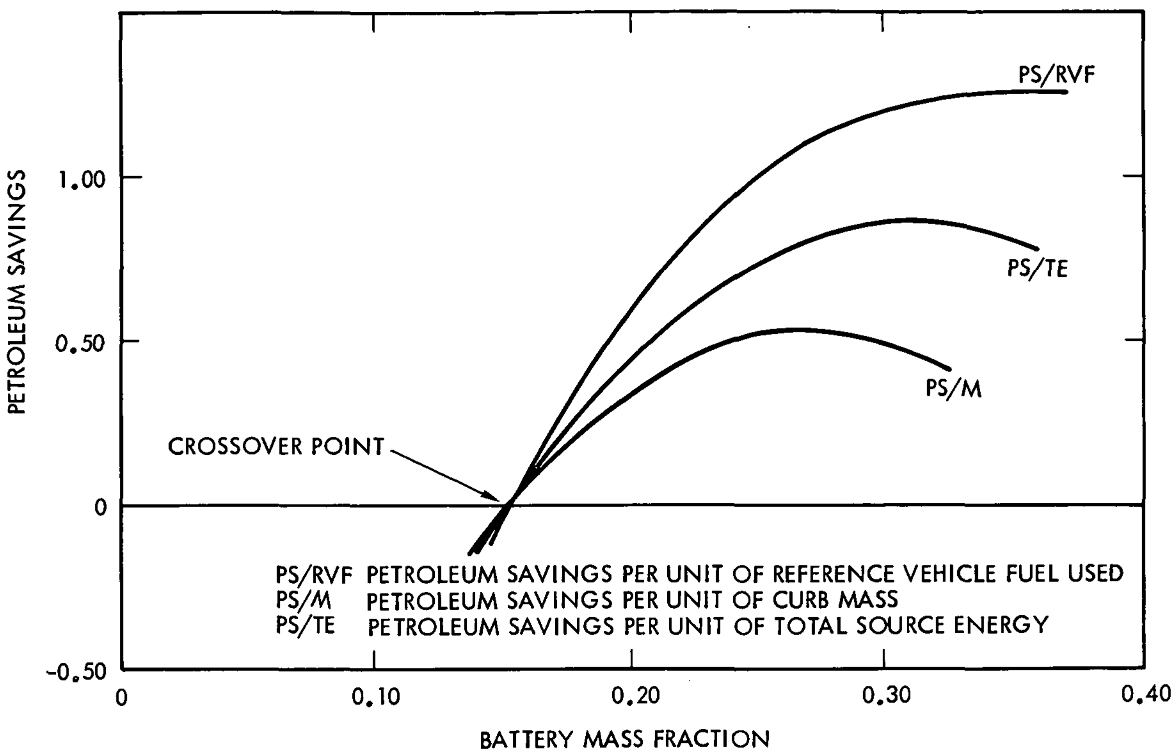


Figure 5-39. Typical Petroleum-Savings Curves

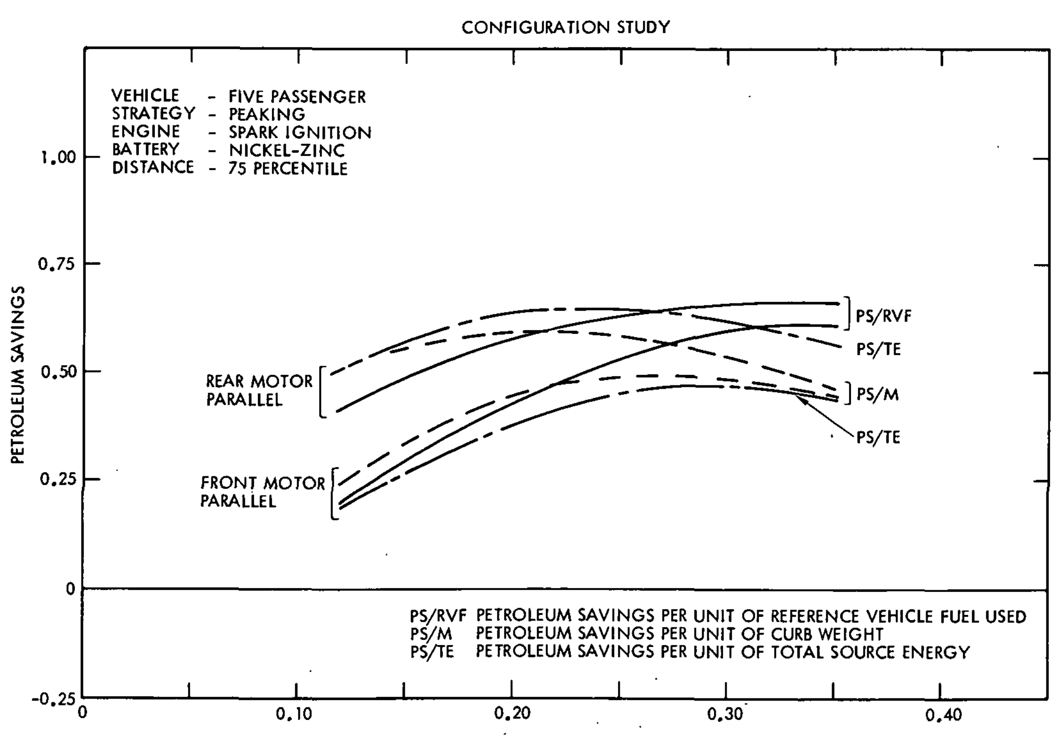


Figure 5-40. Petroleum Savings for Five-Passenger Vehicle, Peaking Strategy

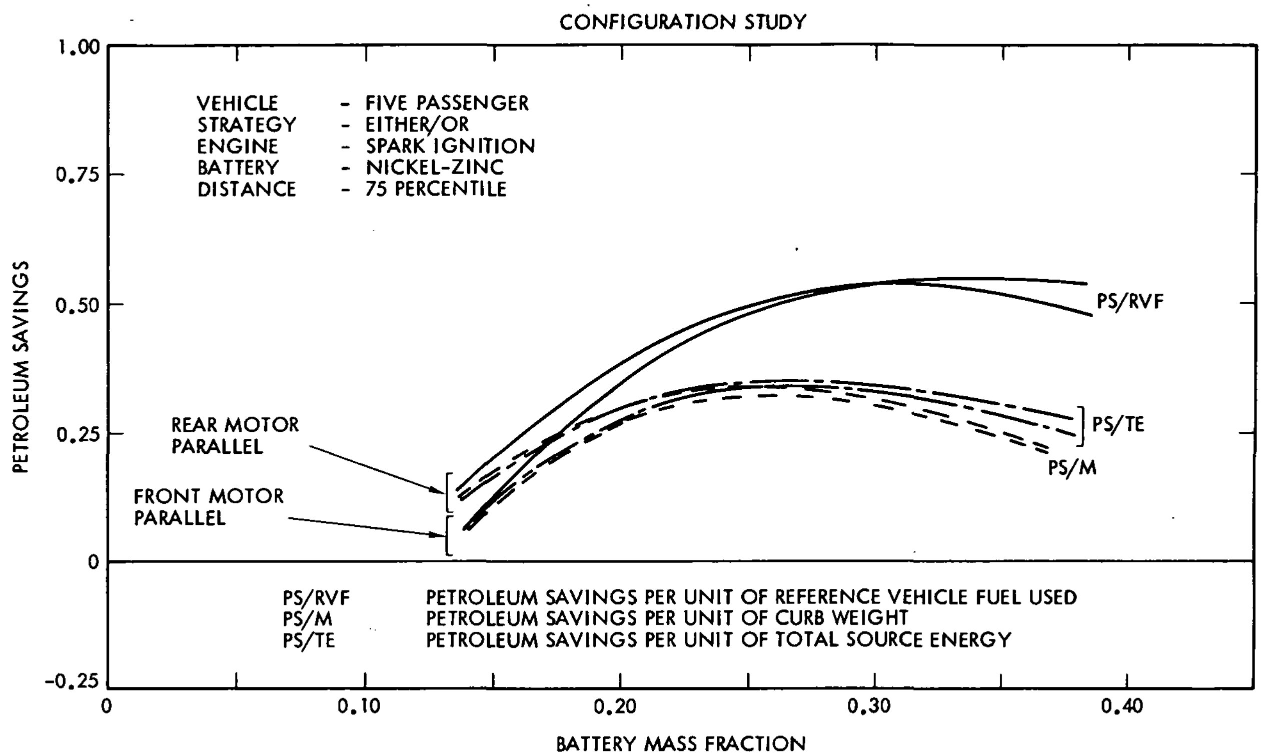


Figure 5-41. Petroleum Savings for Five-Passenger Vehicle, Either/Or Strategy

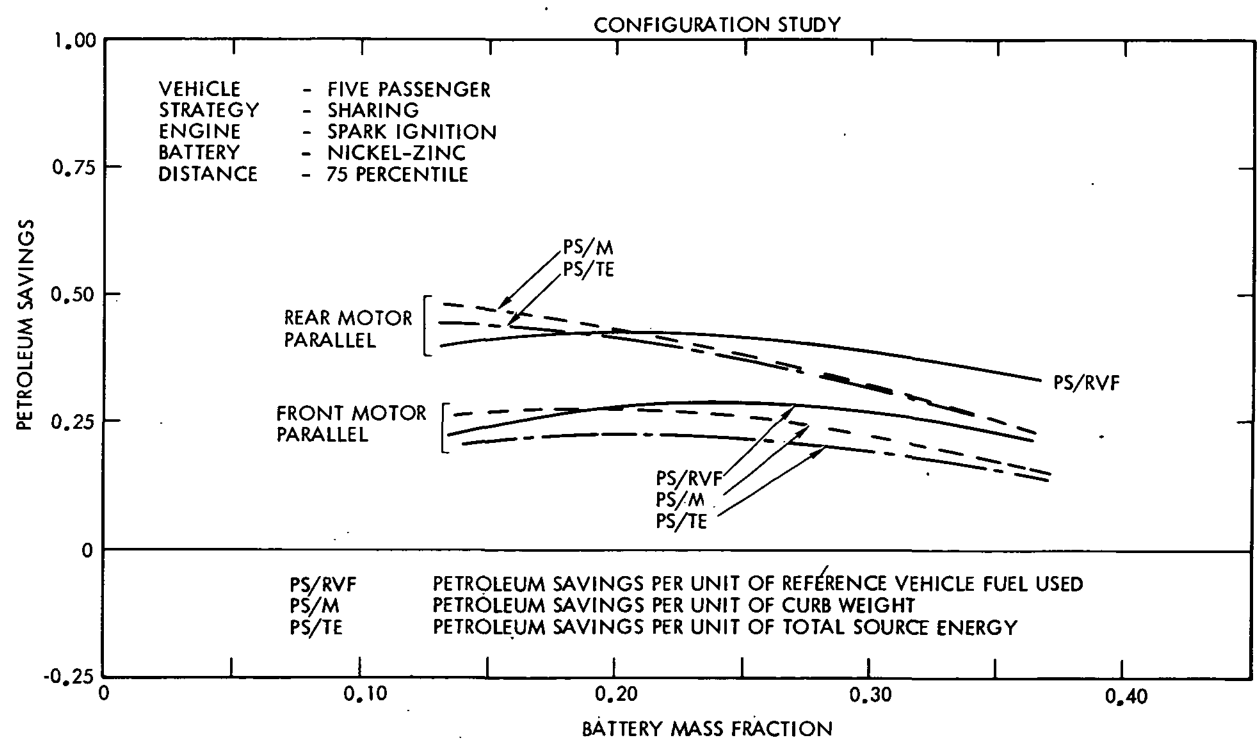


Figure 5-42. Petroleum Savings for Five-Passenger Vehicle, Sharing Strategy

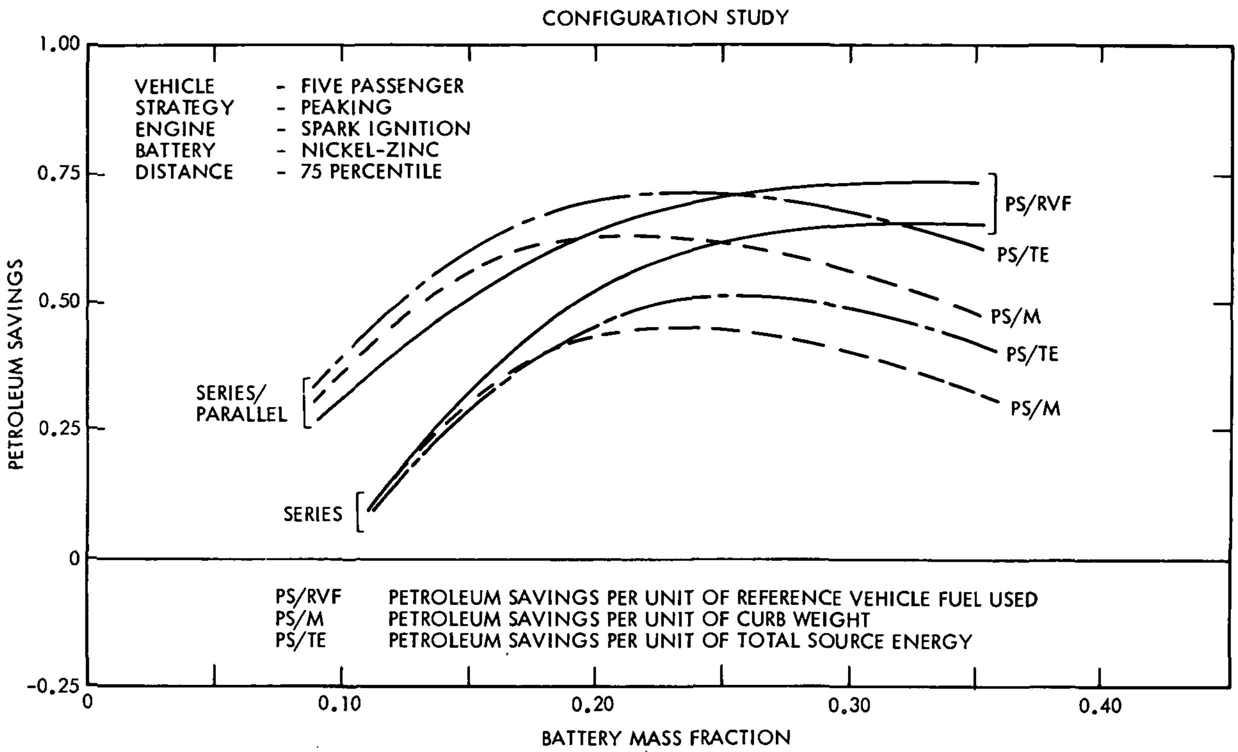


Figure 5-43. Petroleum Savings for Five-Passenger Vehicle, Peaking Strategy

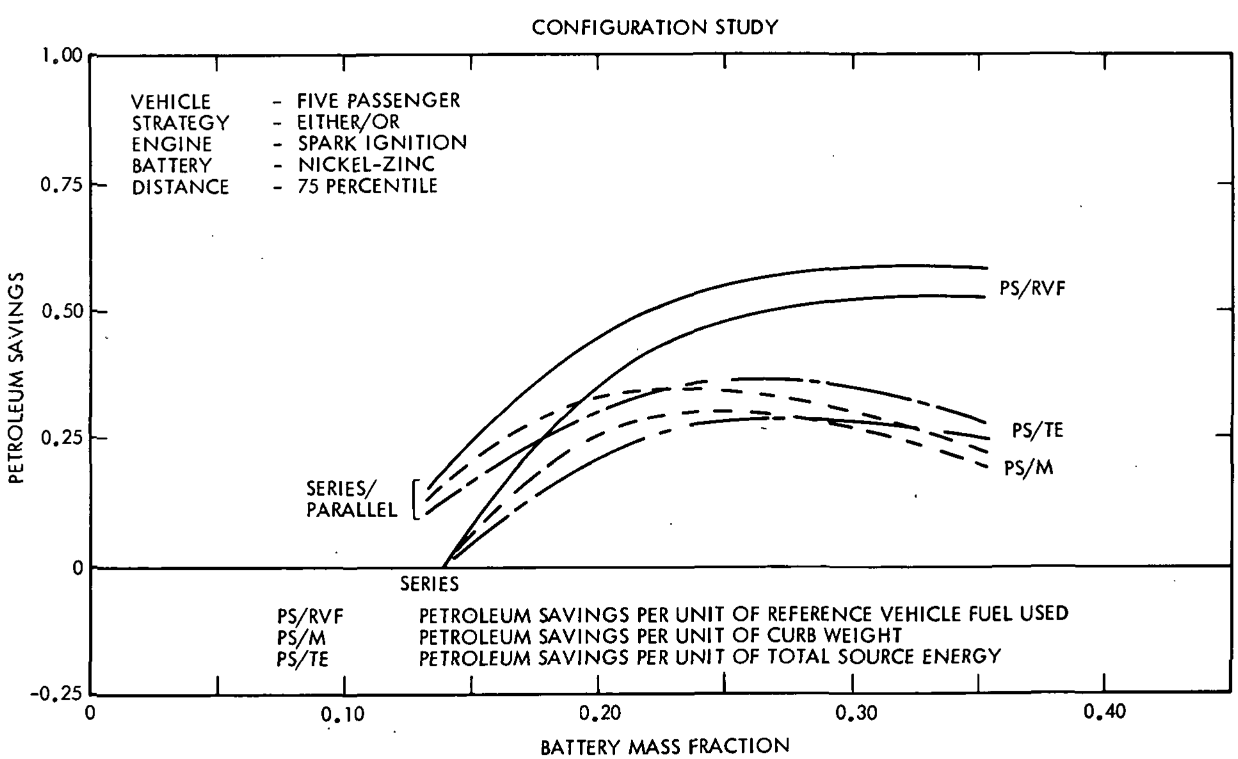


Figure 5-44. Petroleum Savings for Five-Passenger Vehicle, Either/Or Strategy

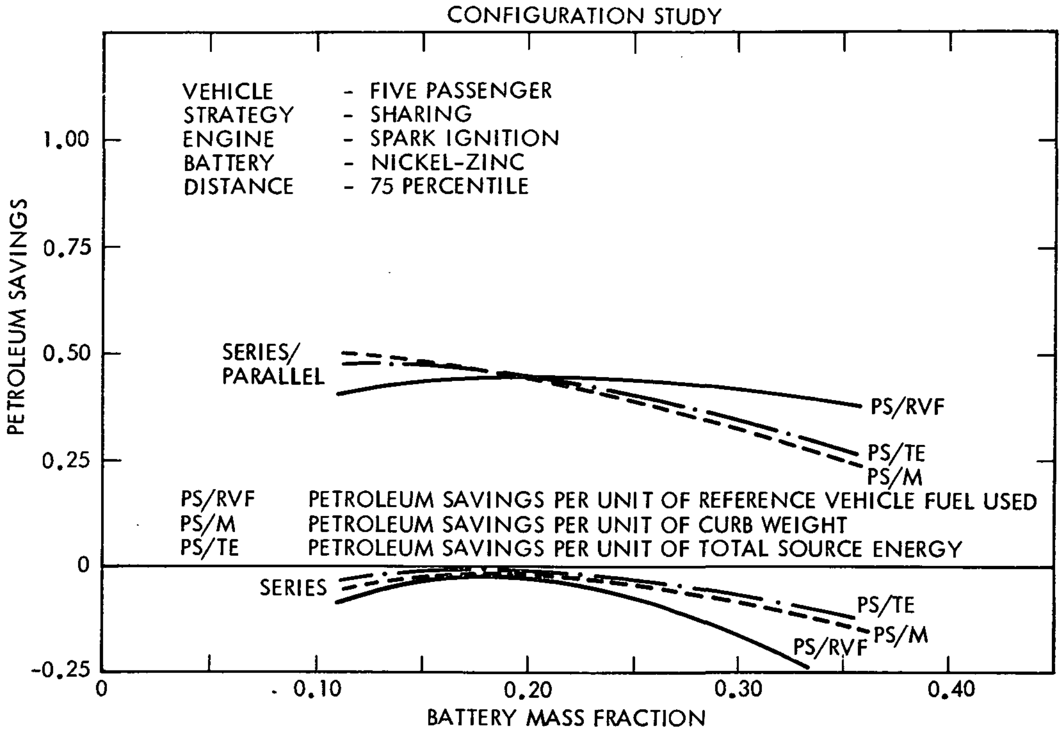


Figure 5-45. Petroleum Savings for Five-Passenger Vehicle, Sharing Strategy

each other, allowing maximum battery energy extraction. The shared strategy (engine always running) uses more fuel than the others and is the least attractive. This is a consequence of the battery capabilities in relation to the mission requirements. Other batteries may require different strategies. The conceptual procedure was described in detail in Section III. The series/parallel hybrid using a peaking energy strategy appears to be the best for all of the vehicles investigated. The rear motor parallel is a close second.

Nine different batteries are shown in the petroleum savings BMF results, Figure 5-48 and Table 5-13. The same power-energy characteristics discussed previously were used. The lead-acid battery is the least attractive with peak petroleum savings of only 40% at the optimum BMF of 23%. Presently under development at JPL is a sealed, bipolar lead-acid battery which shows promise of yielding a specific energy as high as some of the better nickel-zinc batteries and with a specific power many times greater. Initial tests indicate that it will be much stiffer than present lead-acid batteries. The sodium-sulfur and lithum-sulfur batteries appear to be the best of the far-term batteries with an optimum BMF of 21% and a peak petroleum savings of 76%. The Al-air battery should be more suitable for EV operations than for HVs.

The petroleum savings of the HV is strongly dependent on battery characteristics. The most important of these are:

(1) Specific energy.

(2) Specific-energy-to-specific-power ratio.

Table 5-14. Maximum Petroleum Savings for Five-Passenger Vehicles

	PS/RVF	PS/M	PS/TE
Either/Or			
Series	0.53[a]	0.31	0.30
Series/parallel	0.59	0.35	0.38
Front motor parallel	0.55	0.34	0.35
Rear motor parallel	0.54	0.33	0.35
Peaking			
Series	0.66	0.47	0.52
Series/parallel	0.74	0.63	0.72
Front motor parallel	0.62	0.50	0.48
Rear motor parallel	0.67	0.60	0.66
Sharing			
Series	-0.03[b]	-0.03[b]	-0.02
Series/parallel	0.44	0.49	0.48
Front motor parallel	0.27	0.25	0.22
Rear motor parallel	0.41	0.46	0.43

[a]0.53 represents 53% reduction in annual petroleum usage as compared to a conventional heat engine vehicle.

[b]-0.03 represents 3% increase in annual petroleum usage.

Figure 5-49, 5-50 and 5-51 show the effects of battery characteristics on peak petroleum savings and on BMF for peak savings. There is direct correlation between peak petroleum savings and the maximum specific energy of the battery as can be seen in Figure 5-49. The correlation between specific power and the BMF for peak petroleum savings is fairly strong except in the case of the nickel-zinc batteries. It must be remembered that the maximum specific power values were deliberately limited, and this may be the cause of the scatter shown in Figure 5-50.

Figure 5-51 shows the effect of maximum specific power on petroleum savings. This curve shows no detectible correlation. The specific power does not directly affect petroleum savings; rather it affects the BMF which, in turn, influences petroleum savings.

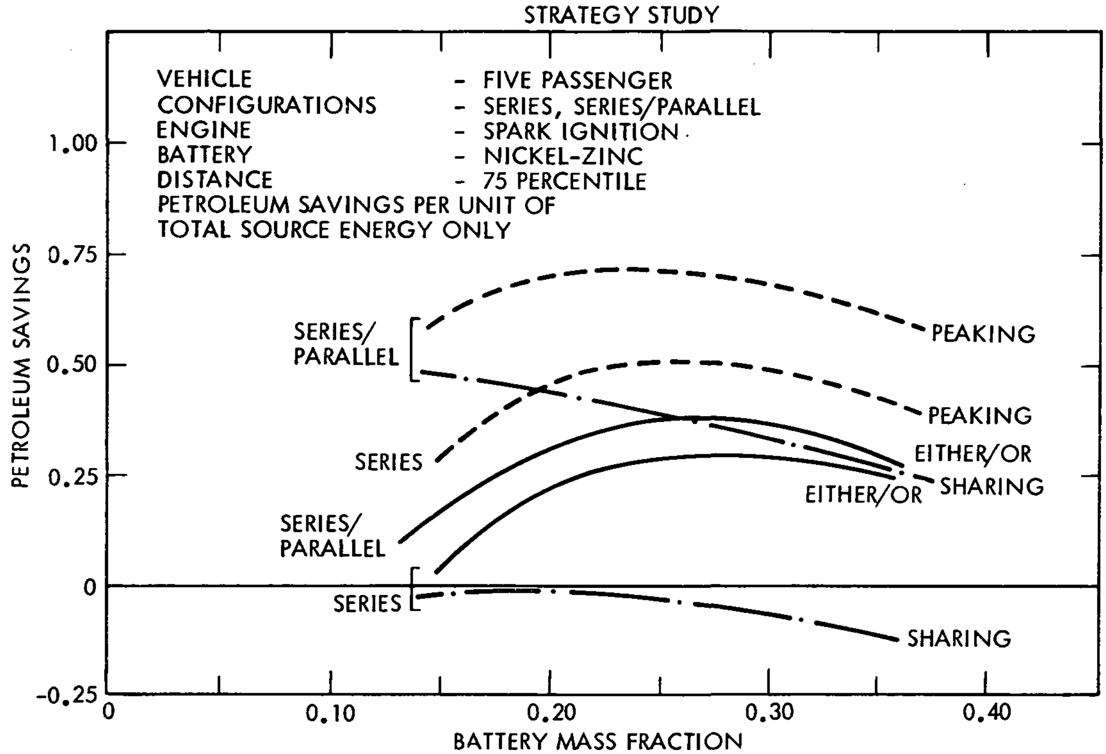


Figure 5-46. Petroleum Savings for Five-Passenger Vehicle, Series and Series/Parallel

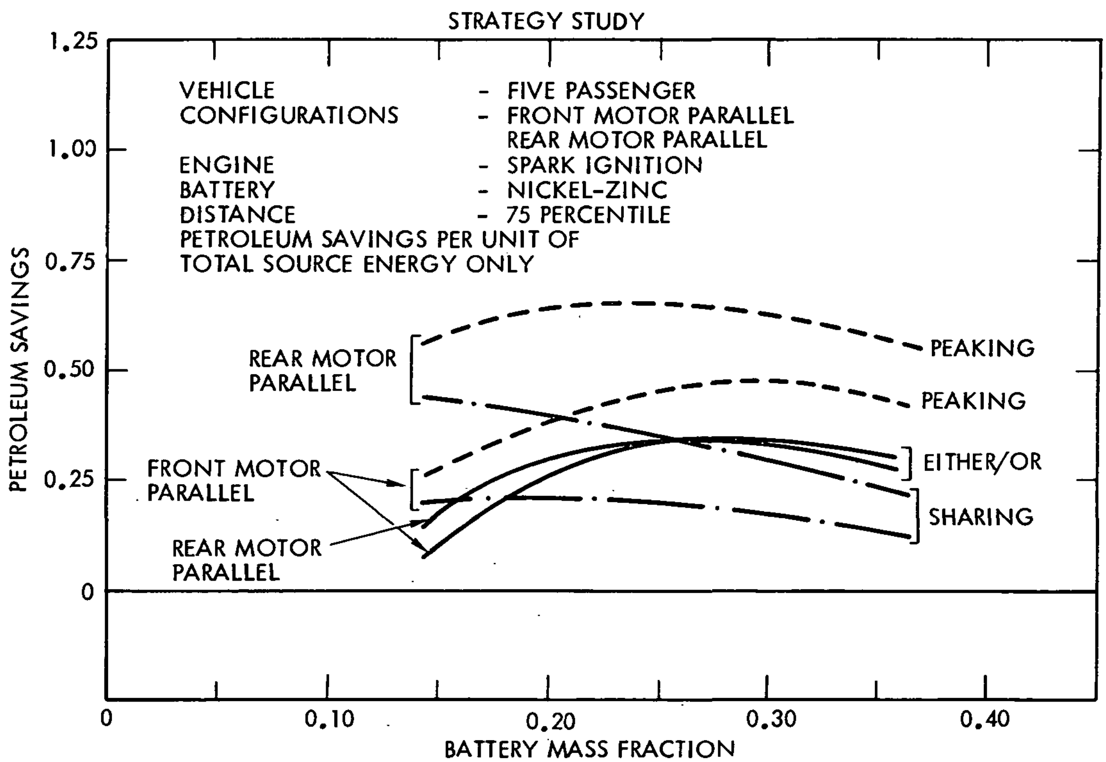


Figure 5-47. Petroleum Savings for Five-Passenger Vehicle, Front Motor and Rear Motor Parallel

Table 5-15. Summary of Strategy Study for Five-Passenger Vehicle

Configuration	Either/or	Peaking	Sharing
Series	0.30[a]	0.52	-0.02
Series/Parallel	0.38	0.72	0.48
Front Motor Parallel	0.35	0.48	0.22
Rear Motor Parallel	0.35	0.66	0.43

[a]0.30 represents a 30% reduction in annual petroleum usage as compared to a conventional heat engine vehicle.

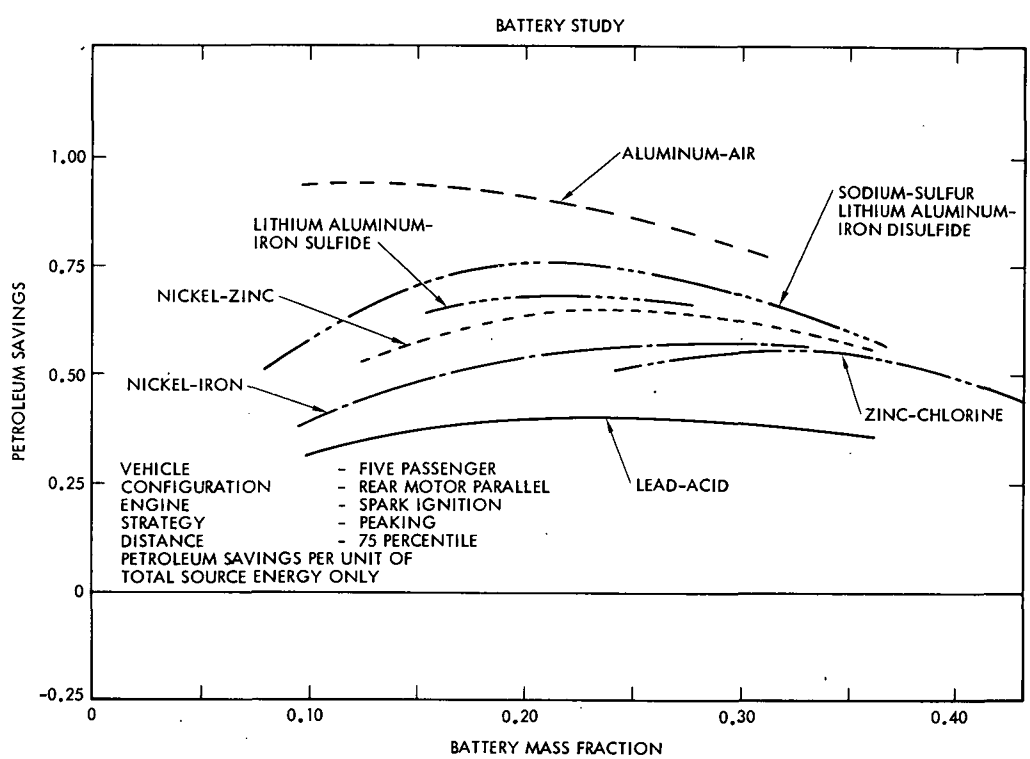


Figure 5-48. Petroleum Savings for Various Batteries, Five-Passenger Vehicle

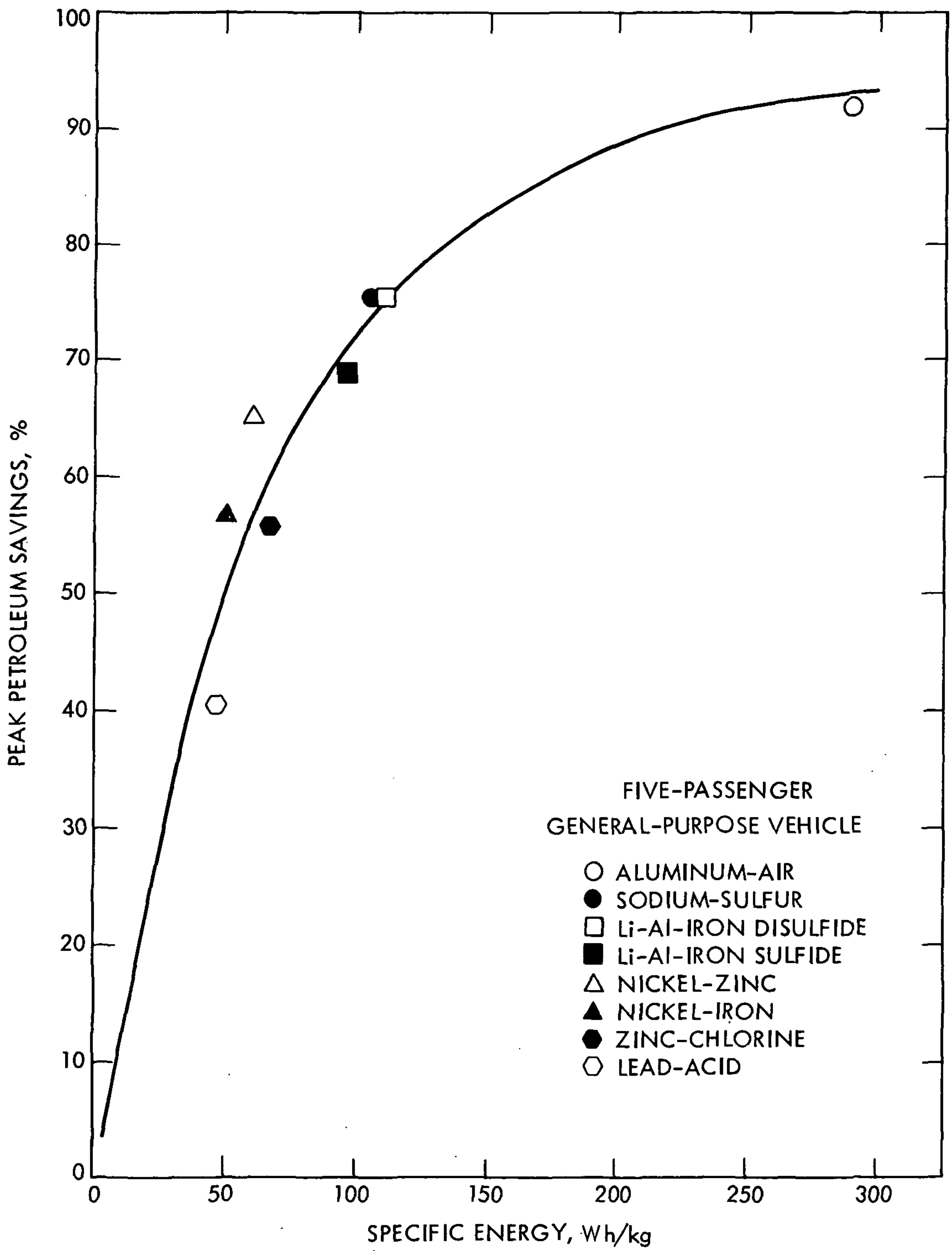


Figure 5-49. Peak Petroleum Savings for Specificity

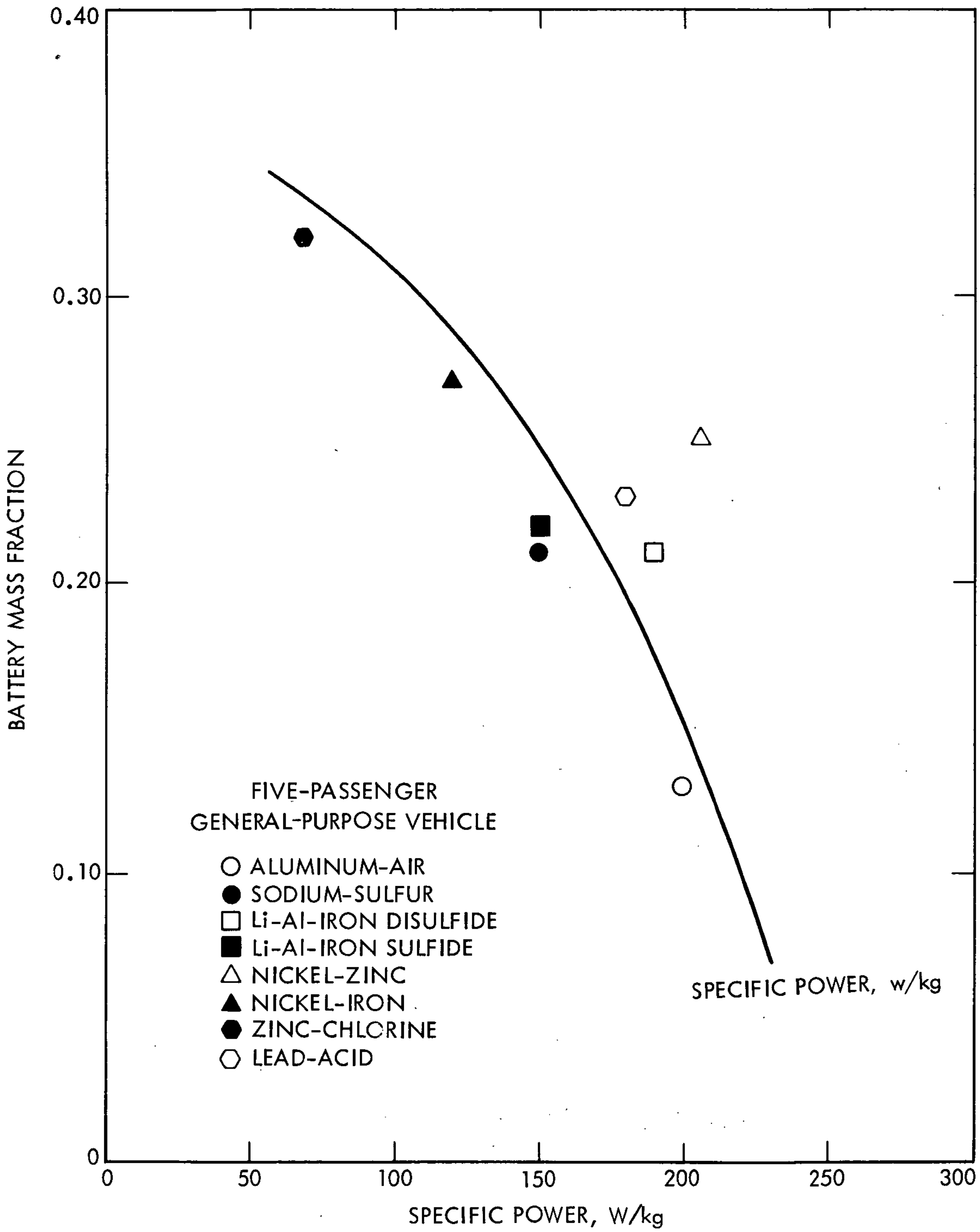


Figure 5-50. Battery Mass Fraction for System Specific Power

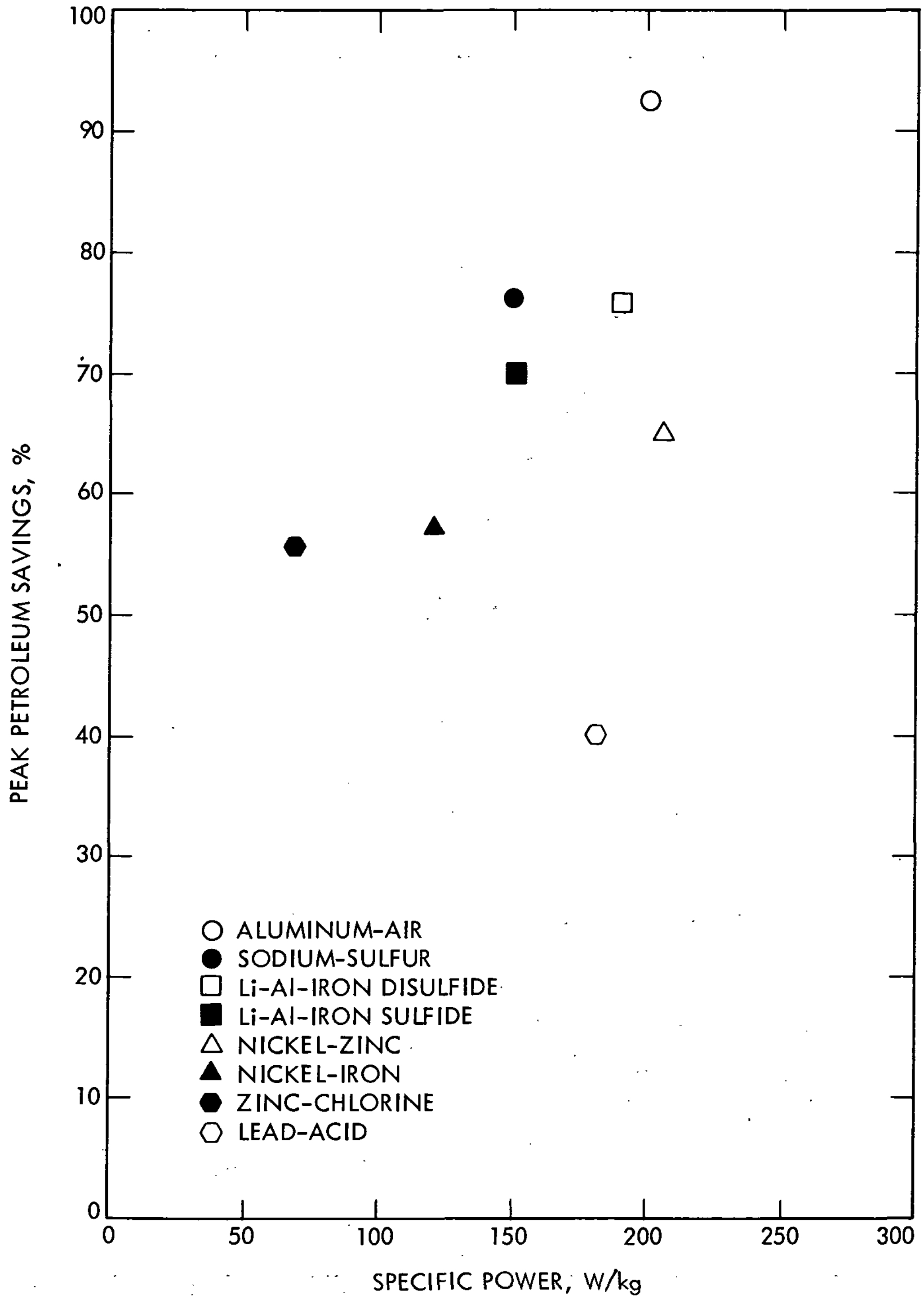


Figure 5-51. Peak Petroleum Savings for Specific Power

Conclusions are that annualized petroleum savings are strong functions of battery specific energy, with near-linear proportionality between 45 and 110 Wh/kg. Optimum HV BMF is a strong function of battery specific power, with near-linear dependence between 70 and 200 Wh/kg.

Although battery characteristics were carefully developed by JPL, the sensitivity of the results to these estimates is well recognized. Higher confidence in battery performance would provide correspondingly improved confidence in petroleum savings predictions. The sodium-sulfur battery appears to have the best specific energy and a close-to-optimum ratio of specific energy to specific power. It is important to note that it is not the characteristics of the sodium-sulfur couple or the details of battery itself, but rather the estimated values of its parameters when measured against the optimum values for performance and mission which point toward its superiority. Other battery couples with similar parameters would appear equally good, or even superior.

In Figure 5-52, the effect of HV engine type is shown. The petroleum savings as a function of BMF is shown for both the spark-ignition engine and for the diesel engine. The diesel engine provides a greater petroleum savings than does the spark-ignition engine, as would be expected. The crossover point for the two engines is nearly equal, so that the crossover point BMF is relatively insensitive to the engine type and primarily controlled by the battery characteristics.

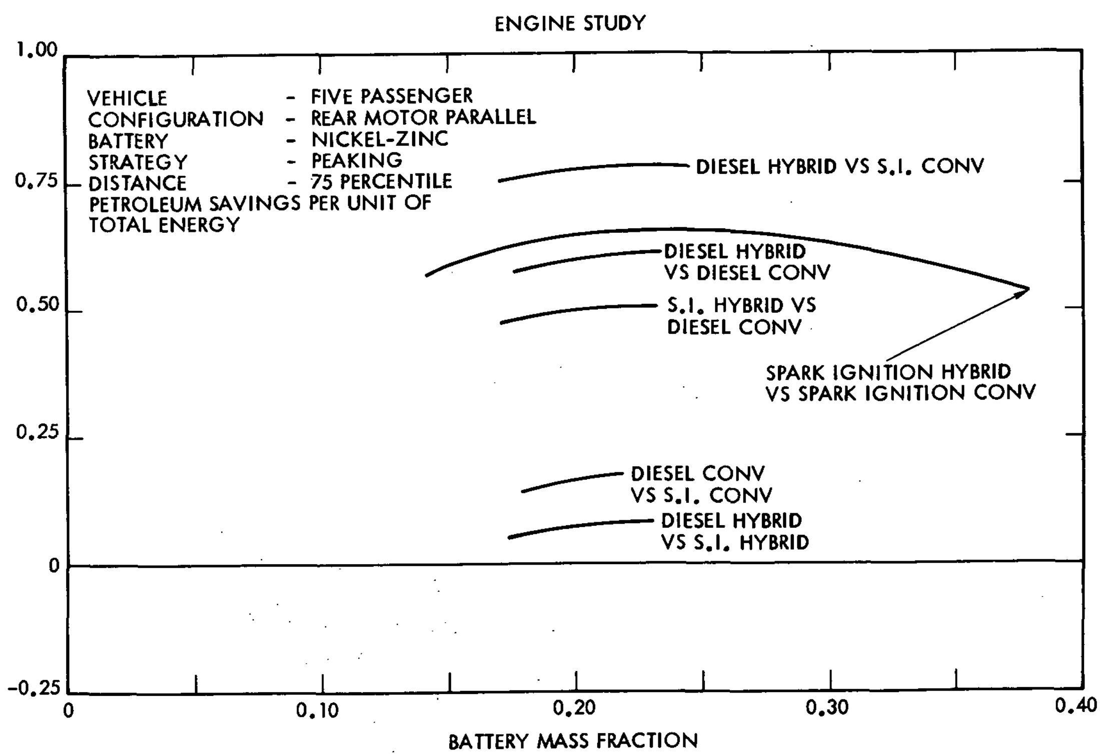


Figure 5-52. Petroleum Savings for Spark-Ignition and Diesel Engines, Five-Passenger Vehicle

Additional comparison between the spark-ignition engine and the diesel engine is shown further in Table 5-16. The first part of this table shows the fuel used per year by the conventional cars and the hybrids. The second part shows the three petroleum savings parameters for six different comparisons. Comparison of a hybrid to a conventional car showed 50 to 75% savings in petroleum. As expected, the largest savings (13 to 19%) are for the diesel hybrid compared to a conventional spark-ignition car. This is because diesel fuel contains 11% more energy than gasoline. The rest of the gain is because of the diesel engine's higher efficiency. Comparing the diesel hybrid to

Table 5-16. Comparison Between Spark-Ignition and Diesel-Powered Five-Passenger Vehicles

Vehicle	Fuel used[a], kg/yr
Diesel hybrid[b]	402.52
Spark-ignition hybrid[b]	481.93
Conventional diesel	1173.07
Conventional spark-ignition	1352.65

	PS/RVF	PS/M	PS/TE
Spark-ignition hybrid vs diesel conventional	0.512	0.459	0.492
Diesel hybrid vs conventional	0.635	0.657	0.755
Diesel hybrid vs diesel conventional	0.580	0.520	0.597
Spark-ignition hybrid vs spark-ignition conventional	0.576	0.596	0.639
Diesel conventional vs spark-ignition conventional	0.133	0.193	0.153
Diesel hybrid vs spark-ignition hybrid	0.165	0.061	0.070

[a]75 percentile annual driving distance.

[b]Peaking, rear motor parallel, 20% battery mass fraction, nickel-zinc battery.

the spark-ignition hybrid reveals a difference in petroleum savings. The PS/M and PS/TE for the comparison of the two hybrids is the lowest petroleum savings on the table. This does not indicate that the diesel engine is an undesirable hybrid, but rather that the gain in petroleum savings going from a spark-ignition engine to a diesel engine in a hybrid is small.

In this section of the power train analysis, the areas of configuration, strategy, battery type, and engine type have been explored with regard to their effect on petroleum savings. The general conclusion is that a diesel-powered rear-motor parallel hybrid using the peaking strategy and a sodium sulfur battery has the best petroleum savings of any of the combinations investigated. These four factors are not, however, the only ones affecting petroleum savings. A number of less-important parameters are explored in the next portion of this section. Also, cost and secondary factors must be considered in the design of a hybrid vehicle.

H. PETROLEUM SAVINGS SENSITIVITY ANALYSES

An important task within the HVA was an analysis of the effects of a number of parameters on petroleum savings. The sensitivity of petroleum savings to variations in the 18 parameters are summarized in Table 5-17. Some parameters can be controlled by vehicle designers (rolling resistance, drag-area product, gear rates, etc.); others result from vehicle use conditions or driving patterns (road grade, annual distance, air conditioning, etc.). In both cases it is important to understand the effects of each parameter on the petroleum savings of the HV. These sensitivities were derived in the same way as the previous results, by simulation over the annual driving pattern. Sensitivities shown are for the five-passenger car. The energy management method used is the peaking strategy because it has the best overall performance of the three investigated. The series/parallel is the chosen configuration with the NiZn battery.

The sensitivity results are summarized in Table 5-8 and ranked according to the slope of the curve at the nominal value of the variable parameter. Most parameters have the units of percent change in petroleum savings per percent change in the variable. The curb weight, for example, is in percent change in petroleum savings per percent weight. (A 1% increase in weight is seen to cause a 0.27% decrease in petroleum savings.) The battery minimum SOC parameter has the units of percent change of petroleum savings per percent change in the minimum SOC. Four parameters have the units of percent change in petroleum savings for a change from off to on. These are air conditioning, other accessories, regenerative braking, and engine idle.

A number of parameters on this list have significant effects on fuel economy and, hence, on petroleum savings. Some have only minor effects and, unless a very large change in the parameter can be made, do not appear to offer significant petroleum savings potential, i.e. minimum engineering development is recommended.

Table 5-17. Slopes of the Sensitivity Curves at Their Nominal Values

Parameter	% Per % Change[a]
Battery minimum state-of-charge	-0.68
Torque converter size	+1.04
Acceleration requirement	-0.10
Battery specific energy	+0.35
Curb weight	-0.27
Yearly driving distance[b]	-0.60
Engine peak power	-0.21
Transmission efficiency	+0.27
Battery specific power	+0.00
Rolling resistance	-0.37
Accessories other than air conditioner[c]	-0.19
Coefficient of drag	-0.40
Frontal area	-0.40
Air conditioning[c]	-0.09
Regenerative braking[c]	+0.09
Differential ratio	-0.06
Transmission gear ratio	+0.01
Continous engine idle[c]	-0.005

[a]The sign in the "% per % change" column describes the effect of an increase in the parameter on petroleum saved over the annual cycle.

[b]Obviously this is not under the designers' control. It is included for reference and information.

[c]Units are % change in petroleum savings for the change from "off" to "on."

The development of high DoD batteries offers the greatest single petroleum saving development analyzed (-0.68%/%). Continuing battery development is required to correct this deficiency, and a primary development recommendation is made. This is also true for battery specific energy improvement (+0.35%/%). Battery specific power improvement is unimportant for peaking strategies, except for those batteries which are strongly affected by DoD.

Secondary development recommendations are made for:

(1) Weight reduction (-0.27%/%).

(2) Transmission efficiency (+0.27%/%).

(3) Rolling resistance (-0.37%/%).

(4) Accessory power management (-0.19%/%).

(5) Drag-area product (-0.40%/%).

Existing technology is adequate to permit improvements in all these areas.

Torque converter size (+1.04%/%) and engine peak power rating (-0.21%/%) have major effects on petroleum savings. These items warrant careful trade-off analysis in HV design. Acceleration requirements (-0.10%/%) and yearly driving distance (-0.60%/%) also have large effects on petroleum savings. Understanding of these HV limitations by users will greatly improve vehicle acceptability.

Regenerative energy recovery is of marginal importance (+0.09%) for petroleum savings, but is significant in providing battery recharge power during normal driving.

Battery minimum SOC (-0.68%/%) and battery specific energy (+0.35%/%) are of first-order importance for petroleum savings. Primary development recommendations are made for both. A minimum SOC of 90% and minimum specific energy of 80 Wh/kg are recommended. Battery specific power (0%/%) does not appear important because of the use of the peaking strategy. Curb weight (-0.27%/%), transmission efficiency (+0.27%/%), rolling resistance (-0.37%/%0), and aerodynamic drag (-0.40%/%) all merit continuing work.

Continous engine idle imposes almost no penalty on petroleum savings. It does, however, simplify HV power control logic and system complexity. An energy management strategy which idles the engine above the power-limited battery SOC appears to be justified, saving frequent on-off-on operations.

I. CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

The results confirm some findings of earlier studies. There are also differences resulting from analysis of configurations not previously investigated and from study of a wider variety of hybrids than before. The use of a single computer program for all hybrids and reference vehicles has produced results which are comparable.

<u>One conclusion is that some vehicles should not be hybridized.</u> Because of its driving pattern, the commuter vehicle is more appropriate as an electric car. The fixed-route van is better suited to all-electric than hybrid operation. If the daily driving distance is beyond that suitable for

all-electric vehicles, the fleet operator might consider relocating the vehicle terminal to reduce daily distance rather than going to either hybrid or heat-engine-only vehicles.

The four-passenger, the five-passenger, and the variable-route van are the only vehicles suitable for hybrid operation from the standpoint of petroleum savings. However, the four-passenger car presents a problem in the volume of the batteries required and the packaging of the components. The conclusion is that the hybrid concept has limited rather than universal applications, and that it is duty-cycle sensitive.

A series/parallel is the preferred configuration. The rear-motor parallel hybrid was second in petroleum savings and the front-motor parallel is the third choice; a series hybrid is the least attractive of the four choices. The series HV still has advocates, however, possibly because of its similarity to an electric vehicle. The series/parallel configuration offers potential for further investigation; its petroleum savings potential should be considered in view of its complexity and cost.

Of the three energy management strategies investigated, the peaking strategy consistently produced the greatest petroleum savings. The sharing strategy had the lowest savings and sometimes resulted in negative savings (waste). The peaking strategy combines high battery use and relatively small components to yield superior petroleum savings.

The aluminum air battery had the best petroleum savings of all of the batteries simulated in this study. (Petroleum consumed in manufacturing the aluminum, however, was not considered.) This battery may not be appropriate for HVs because its specific power and specific energy projections allowed nearly unassisted operation. In typical driving cycles the heat engine was used only five times a year, not justifying the expense of carrying the conventional power train. The next-best batteries are sodium-sulfur and lithium aluminum-iron disulfide batteries. These are suitable for hybrids with petroleum savings of 76% using a battery mass fraction of only 21%. The nickel-zinc battery has savings in the middle of the battery range and the lead-acid battery had the poorest performance. In several cases, the lead-acid battery results in negative petroleum savings. Of the eight batteries investigated, the nickel-zinc battery is best suited for use in a hybrid vehicle in the near term. Na-S and both Li-S batteries have potential for the longer term.

The ideal HV battery has enough specific power over the full SOC range to maintain the energy limit. Such a combination of energy and power results in the lightest car and the greatest petroleum savings. The hybrid vehicle allows the use of batteries with specific power and specific energy characteristics not suitable for electric vehicles, while still producing significant petroleum savings. This makes the Ni-Zn a good HV battery for the near term. Regardless of the particular battery couple employed, an acceptable specific energy of 80 Wh/kg at or below specific power level of 100 W/kg is a reasonable development goal for hybrid batteries. For the configuration, batteries, and strategies studied, petroleum saving is nearly proportional to battery specific energy. Optimum BMF is strongly dependent on battery specific power.

The diesel engine hybrid offers better petroleum savings than the spark-ignition engine. The savings, however, are not as great as might be expected due to use of the same performance criteria for both cars. (The diesel engine is heavier than the spark-ignition engine, but this does not result in a significant increase in curb weight, particularly in the HV.)

Yearly driving distance is an important factor in hybrid vehicle design and petroleum savings. If the distance is less than the 50th percentile distance (13000 km), use of the heat engine is low enough to question the use of the hybrid concept. When the annual distance is near the 90th percentile mark (30,000 km), the amount of petroleum saved is compromised by the additional mass of the battery and the electrical system. There is a mid-range appropriate for hybrids.

The sensitivity study indicates that the minimum SOC and specific energy are key battery parameters. Rolling resistance, torque converter size, curb weight, transmission efficiency, and aerodynamic drag are also important. The road grade and the performance requirements on grades have strong effects on both petroleum savings and components sizing. Unfortunately, the usual methods of simulating and testing vehicles ignore this and the results rarely reflect actual vehicle operation.

With proper design and use, HV petroleum savings can be realized in the 50 to 70% range. However, it should be noted that it is also possible to have hybrid vehicles with negative petroleum savings.

2. Recommendations

It is recommended that future plans for the development of hybrid vehicles include the following items.

(1) Use of the rear-motor-parallel configurations.

(2) Additional study and possible use of the series/parallel configuration.

(3) Energy management strategy used on advanced hybrid should be limited to the peaking type.

SECTION VI

THE GENERAL ELECTRIC COMPANY HYBRID TEST VEHICLE

A. INTRODUCTION

The General Electric Company (GE) developed an HTV under a contract funded by the Department of Energy with technical management by JPL. It was constructed and tested by GE and delivered in April 1983 to enter a comprehensive JPL test program.

Both technical design and hardware use information have resulted from the HTV program. Experience from the GE program and the early phase of JPL testing has identified some design considerations that would produce a next-generation HV with a greater potential for actual commercial use.

B. THE HYBRID POWER TRAIN

The HTV propulsion system (Figure 6-1) uses two power sources, a separately excited dc motor and a gasoline engine. The peaking strategy is used and power is supplied by the heat engine or electric motor alone or in combination, depending on the type of driving, power demand, and battery SOC. A hydraulically actuated engine clutch is used to couple and decouple the engine into the power train within 400 ms in an on/off mode. The clutch is a standard dry-friction type, sized to accommodate rapid closure.

The electric motor idles when the vehicle is at rest and is always the source of starting power. The electric motor clutch (drive clutch) modulates the flow of power as the vehicle is started. Clutch modulation is controlled by the microcomputer software. Torque from the electric motor and heat engine is delivered to the transmission input shaft via Morse chain drives. Transmission shifting is controlled using five electrically actuated hydraulic valves positioned outside the transmission. Electrical signals are sent to the valves by the microcomputer.

Only the electric motor is used below 18.2 km/h, regardless of the power demand or battery SOC. Below a specified vehicle speed, VMODE[9], the motor is the primary power source. Above the VMODE speed, the heat engine is the primary power source. When the power demanded by the operator is greater than the power capability of the primary propulsion unit, both units operate and share the load. Combined operation also occurs when the battery SOC reaches 20% and battery charging becomes necessary. In this case, the engine charges

[9]VMODE speed is primarily a function of battery SOC. At 100% SOC it is 64 km/h. As the SOC declines, it lowers in value until, at 20% SOC, it has been reduced to 18.2 km/h.

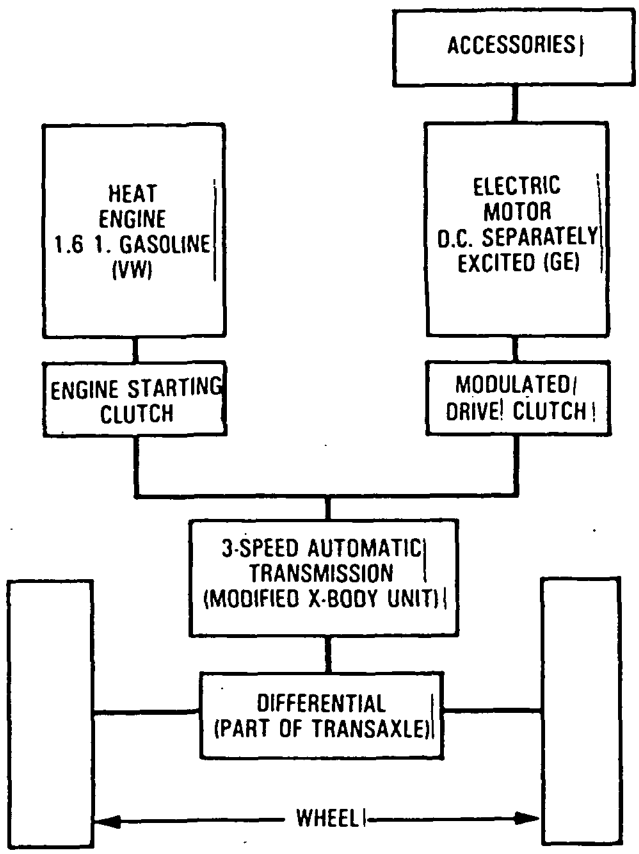


Figure 6-1. General Electric HTV Propulsion System

the battery pack by driving the dc motor as a generator, when excess engine capacity is available after meeting the accelerator pedal demand of the driver. The battery is not recharged above 30% SOC.

C. RESULTS OF DESIGN EXPERIENCE

After completion of the program, it became apparent from the development experience that the vehicle power train was overly complex so that it would be difficult to produce a hybrid that was reliable and maintainable. In future design studies consideration should be given to trading some optimization of performance for simplicity of design.

As discussed in Section V, an engine "always-on" logic is not overly detrimental to petroleum savings. The annualized figure was -0.005%/%. This has suggested a simplified power control logic which would reduce system complexity without unduly penalyzing petroleum savings. This strategy would be to command the engine on only once. Microprocessor logic would be greatly

simplified, repetitive clutch operations would be unnecesary, and reliability and maintainability would be improved. This concept is fully compatible with the parallel peaking strategy. Investigation of the concept for future vehicle designs is recommended.

The required dependence on the electric motor below 18.2 km/h is also considered a deficiency. Any parallel hybrid should be capable of operation down to zero speed on either power source. This may be accomplished either by design or by a fail-soft energy management strategy which allows sufficient driver interaction to accomplish the required change in logic.

D. BATTERY CAPACITY

The HTV battery was designed to have a capacity of 105 A-h at a 3-h rate with a voltage-drop limitation at high-power output. Although the battery, as delivered, met these requirements, its ultimate performance in the HTV with the 400- to 500-A peak current required when driving the Federal Urban Cycle resulted in an actual realized capacity of about 40% of the 3-h rate. This resulted in a significant reduction of the projected petroleum saving performance.

In HV design the petroleum saving results primarily from the available electric energy and its optimized use. Battery sizing must be carefully considered, and its performance specifications be based on its use in an HV system. The method described in this report for BMF optimization was designed to accomplish this objective.

E. ACCESSORY POWER REQUIREMENTS

In any motor vehicle significant power is required to drive accessories. This is significant in an HV because, depending on the design mechanization, much electrically stored energy might be required for accessories, thus affecting the overall vehicle performance as a hybrid. Experience from the HTV has emphasized this fact. At idle periods and during high electric use, the accessories were driven only by the electric motor. Even though the HTV program made a significant and successful effort to reduce accessory loads, the performance of the final vehicle was definitely compromised by high loads. On future designs this could be improved by minimizing accessory requirements, by driving strategy considerations, and by use of accessory speed control devices as described in Section III.

F. BATTERY STATE-OF-CHARGE MEASUREMENT

Lead-acid batteries must be protected against excessive discharge to avoid reduction in life. A hybrid design that uses the heat engine to recharge the battery requires accurate measurement of the battery SOC. Current measurement technology and that used on the HTV may not be adequate to meet this requirement. For future designs the SOC measurement requirement must be considered in system design and in the specification of SOC measurement components.

G. COMPONENT SELECTION

Most of the component design failures and problems encountered on the HTV involved problems with standard automative parts or technology application affecting HV-specific conditions. Failures were encountered with clutches, shafts, and the power-transmission chain because of transient conditions or fast operating rates in the HTV application. Mechanization of the automatic computer-controlled transmission shifting with external valves proved difficult, but was finally achieved and the feasibility of smooth computer-controlled power blending between engine and motor was demonstrated. Problems were encountered with transmission internal loads caused by downshifting during regenerative braking, a non-standard condition.

SECTION VII

REFERENCES

1. Route, W.D., Amann, C.A., and Gallopoulos, N.G., Developments in Automotive Technology, Fuels, and Lubricants, GMR-3863R F&L-736, General Motors Research Laboratories, November 1981.

2. Kurtz, D., and Levin, R., "EHV Systems Technology - A Look at the Principles and Current Status," IEEE Transactions, February 1983.

3. Surber, F., Assessment of the Potential of Hybrid Vehicles, JPL Publication 80-13, Jet Propulsion Laboratory, Pasadena, California, March 1980.

4. Hardy, K., Advanced Vehicle Subsystem Technology Assessment, JPL Internal Publication D-230, Jet Propulsion Laboratory, Pasadena, California, January 1983.

5. McDonald, A.T., "Reducing Battery Costs for Electric Vehicles Through Optimal Depth of Discharge," EVC No. 8142, EVC Symposium VI, October 1981.

6. Hartman, J.L., Cairns, E.J., and Heitbrink, E.H., "Electric Vehicles Challenge Battery Technology," Proc. Energy Technology V, Washington, D.C., February 1978.

7. Ragone, D.V., "Review of Battery Systems for Electrically Powered Vehicles," Paper 68053, Mid-year Meeting, Detroit, Michigan, May 1968.

8. Bryant, J.A., Hardy, K.S. Livingston, R., and Sandberg, J., Upgraded Demonstration Vehicle Task Report, JPL Publication 81-98, Jet Propulsion Laboratory, Pasadena, California, October 1981.

9. Zeldin, B., Environmental and Control Subsystems for Electric and Hybrid Vehicles, JPL Publication 82-17, Jet Propulsion Laboratory, Pasadena, California, April 1982.

10. U.S. Department of Transportation, Characteristics of 1977 Licensed Drivers and Their Travel, Report No. 1, Nationwide Personal Transportation Study, Washington, D.C., 1980.

11. U.S. Department of Transportation, Nationwide Personal Transportation Study, Reports 1-10, Washington, D.C., May 1974.

12. Office of Technology Assessment, Changes in the Future Use and Characteristics of the Automobile Transportation System, Washington, D.C., February 1979.

13. Schwartz, H.J., "The Computer Simulation of Automobile Use Patterns for Defining Battery Requirements for Electric Cars," Fourth International Electric Vehicle Symposium, Dusseldorf, Germany, 1976.

14. Surber, F.T., and Deshpande, G.K., Hybrid Vehicle Potential Assessment, Vol. II: Mission Analysis, JPL Internal Report, Jet Propulsion Laboratory, Pasadena, California, 1979.

15. Holcomb, M.C., Greene, D.L., and Roberts, G.F., Motor Vehicle MPG and Market Shares, ORNL 81/4, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 1982.

16. Solomon, D., Accidents on Main Rural Highways Related to Speed, Driver, and Vehicle, U.S. Department of Commerce, Washington, D.C., July 1964.

17. Park, R., and Krout, S., Road Grades - U.S. Distribution of Auto Vehicle Miles, Raytheon Service Company, Cambridge, Massachusetts, May 1974.

SECTION VIII

BIBLIOGRAPHY

Bryant, J.A., Hardy, K.S., Livingston, R., and Sandberg, J., Upgraded Demonstration Vehicle Task Report, JPL Publication 81-98, Jet Propulsion Laboratory, Pasadena, California, October 1981.

Energy Review, Data Resources Inc., Summer 1982, Lexington, Massachusetts.

Hardy, K., Advanced Vehicle Subsystem Technology Assessment, JPL Internal Publication D-230, Jet Propulsion Laboratory, Pasadena, California, January 1983.

Hartman, J.L., Cairns, E.J., and Heitbrink, E.H., "Electric Vehicles Challenge Battery Technology," Proc. Energy Technology V, Washington, D.C., February 1978.

Holcomb, M.C., Greene, D.L., and Roberts, G.F., Motor Vehicle MPG and Market Shares, ORNL 81/4, Oak Ridge National Laboratory, Oak Ridge, TN, March 1982.

Kurtz, D.W., The DOE Electric Test Vehicle, JPL Publication 81-93, Jet Propulsion Laboratory, Pasadena, California, December 1981.

Kurtz, D., and Levin, R., "EHV Systems Technology - A Look at the Principles and Current Status," IEEE Transactions, February 1983.

McDonald, A.T., "Reducing Battery Costs for Electric Vehicles Through Optimal Depth of Discharge," EVC No. 8142, EVC Symposium VI, October 1981.

Office of Technology Assessment, Changes in the Future Use and Characteristics of the Automobile Transportation System, Washington, D.C., February 1979.

Park, R., and Krout, S., Road Grades - U.S. Distribution of Auto Vehicle Miles, Raytheon Service Company, Cambridge, Massachusetts, May 1974.

Prospects for Electric Vehicle Mass Production, Vol. I., Arthur D. Little, Inc., Cambridge, Massachusetts, December 1980.

Ragone, D.V., "Review of Battery Systems for Electrically Powered Vehicles," Paper 68053, Mid-year Meeting, Detroit, Michigan, May 1968.

Route, W.D., Amann, C.A., and Gallopoulos, N.G., Developments in Automotive Technology, Fuels, and Lubricants, GMR-3863R F&L-736, General Motors Research Laboratories, November 1981.

Schwartz, H.J., "The Computer Simulation of Automobile Use Patterns for Defining Battery Requirements for Electric Cars," Fourth International Electric Vehicle Symposium, Dusseldorf, Germany, 1976.

Solomon, D., Accidents on Main Rural Highways Related to Speed, Driver, and Vehicle, U.S. Department of Commerce, Washington, D.C., July 1964.

Steffens, F., "Development of a Hybrid Electric-Vehicle System," Electric Vehicle Developments Journal, September 1981.

Surber, F., Assessment of the Potential of Hybrid Vehicles, Publication 80-13, Jet Propulsion Laboratory, Pasadena, California, March 1980.

Surber, F.T., and Deshpande, G.K., Hybrid Vehicle Potential Assessment, Vol. II: Mission Analysis, Report 5030-345, Jet Propulsion Laboratory, Pasadena, California, 1979.

Taylor, D.F. and Siwek, E.G., "The Dynamic Characterization of Lead-Acid Batteries for Vehicle Application," Paper 730252, International Automotive Engineering Congress, January 1973.

U.S. Department of Transportation, Characteristics of 1977 Licensed Drivers and Their Travel, Report No. 1, Nationwide Personal Transportation Study, Washington, D.C., 1980.

U.S. Department of Transportation, Nationwide Personal Transportation Study, Reports 1-10, Washington, D.C., May 1974.

Zeldin, B., Environmental and Control Subsystems for Electric and Hybrid Vehicles, JPL Publication 82-17, Jet Propulsion Laboratory, Pasadena, California, April 1982.

Part Three
Appendices

APPENDIX A

GLOSSARY

Annual pattern	Accumulated yearly mileage of a vehicle composed of daily cycles and individual trips
AVKT	Annual vehicle kilometers traveled
BMF	Battery mass fraction (mass of traction battery divided by vehicle curb mass)
BSFC	Brake specific fuel consumption
Cell	Daily travel distance
Configuration	Physical arrangement of vehicle subsystems
CVT	Continuously variable transmission
Daily cycle	Use pattern of a vehicle over 24-h period (contains individual trip times and lengths)
DoD	Battery depth of discharge
Drivetrain	Transmission, differential, clutches, torque converter, and gearbox
Deficiency vector	Two-component vector difference between battery capability (power and energy) and vehicle requirements (power and energy)
Electric range	Distance a HV can travel primarily using its batteries
Energy density	Battery energy divided by battery volume, ($Wh\text{-}\ell^{-1}$)
Energy management strategy	Logic (software) which determines how power is allocated between electrochemical and petrochemical energy storage subsystems
Engine peaking strategy	Method by which electrochemical system supplies basic road load and petrochemical system supplies the peaks
HPTM	Hybrid power train mule
HTV	General Electric Hybrid Test Vehicle

HV	Hybrid vehicle deriving propulsion energy from two sources, wall-plug electrical energy and petrochemical (gasoline or diesel) energy
Motor peaking strategy	Method by which petrochemical system supplies basic road load and electrochemical system supplies the peaks
Parallel configuration	Arrangement of either the electrochemical or the petrochemical system to supply mechanical power to the wheels
Petroleum savings	Difference between petroleum consumption of a reference vehicle and a hybrid which both have the same performance and driving pattern
Power density	Battery peak power available divided by battery volume, $(W\text{-}\ell^{-1})$
Power train	Components comprising the drivetrain, power plant, drive axle, and energy storage subsystems
Recuperation	Dwell period during which a discharged battery partially recovers, but is neither charged nor discharged (except perhaps for self-discharge)
Reference vehicle	Conventional (Otto-cycle engine) vehicle used for reference petroleum consumption
Regeneration	Conversion of vehicle kinetic energy to electrical energy and its reintroduction into the traction battery, usually at very high recharge rates
Secondary battery	Battery designed for repeated discharge-charge cycles
Series configuration	Arrangement in which wheel power must be supplied by the electric motor
SOCI	Battery state-of-charge indicator
Specific energy	Battery energy divided by battery mass (Wh/kg)
Specific power	Battery power divided by battery mass (W/kg)
TBM	Test-bed mule

Traction battery	Battery designed to provide tractive power
Transparey	Independence of vehicle performance with battery DoD
Utility functions	Petroleum savings per unit annual vehicle energy expended; petroleum savings per unit reference vehicle fuel used; petroleum savings per unit vehicle mass
Vehicle energy expended	Total amount of energy (petrochemical plus electrochemical) expended annually by the HV

APPENDIX B

This appendix consists of typical 24-hour driving cycles for each mission in tabulated form. Daily distance, number of trips, starting time, and type of cycle used are shown. A typical annual driving pattern (22,176 km) for the general-purpose vehicle mission is given as well as a typical daily schedule in graphical format.

Twenty-four-hour Driving Cycle for the Two-Passenger Commuter Vehicle

Daily Distance, km		No. of Trips	Trip No.	Starting Time	Distance, km	Cycle(s)
1.	4	2	1	7:30 a.m.	2.0	U
			2	3:32 p.m.	2.0	U
2.	12	2	1	9:30 a.m.	6.0	U
			2	2:40 p.m.	6.0	U
3.	20	4	1	7:30 a.m.	1.2	U
			2	12:32 p.m.	12.0	U
			3	13:27 p.m.	0.8	U
			4	16:28 p.m.	2.4	U
4.	28	3	1	7:30 a.m.	10.0	U
			2	4:30 p.m.	8.0	U
			3	5:30 p.m.	10.0	U
5.	40	4	1	7:30 a.m.	10.0	U
			2	4:30 p.m.	10.0	U
			3	6:30 p.m.	12.0	U
			4	8:30 p.m.	8.0	U
6.	56	5	1	7:30 a.m.	10.0	U
			2	10:30 a.m.	12.0	U
			3	2:30 p.m.	12.0	U
			4	4:30 p.m.	10.0	U
			5	7:30 p.m.	6.0	U
			6	9:00 p.m.	6.0	U
7.	72	4	1	8:00 a.m.	10.0	U
			2	5:00 p.m.	10.0	U
			3	7:00 p.m.	26.0	U/H
			4	9:00 p.m.	26.0	U/H
8.	88	3	1	8:30 a.m.	4.0	U
			2	8:45 a.m.	40.0	U/H/U
			3	5:30 p.m.	44.0	U/H/U
9.	112	5	1	7:30 a.m.	10.0	U
			2	4:30 p.m.	10.0	U
			3	6:00 p.m.	40.0	U/H/U
			4	7:30 p.m.	12.0	U
			5	9:00 p.m.	40.0	U/H/U

U refers to EPA Urban
H refers to EPA Highway

Twenty-four-hour Driving Cycle for the General-Purpose Vehicles

Daily Distance, km		No. of Trips	Trip No.	Starting Time	Distance, km	Cycle(s)
1.	4	2	1	7:30 a.m.	2.0	U
			2	3:30 p.m.	2.0	U
2.	12	2	1	9:30 a.m.	6.0	U
			2	2:40 p.m.	6.0	U
3.	20	4	1	7:30 a.m.	1.2	U
			2	12:32 p.m.	12.0	U
			3	1:27 p.m.	0.8	U
			4	4:28 p.m.	2.4	U
4.	28	2	1	8:30 a.m.	12.0	U
			2	3:40 p.m.	12.0	U
5.	40	4	1	6:30 a.m.	7.2	U
			2	1:43 p.m	4.0	U
			3	3:30 p.m.	12.0	U
			4	10:45 p.m.	12.0	U
6.	56	5	1	8:30 a.m.	24.0	U/HU
			2	9:45 a.m.	7.2	U
			3	10:43 a.m.	4.0	U
			4	5:50 p.m.	12.0	U
			5	7:45 p.m.	7.2	U
7.	72	4	1	8:30 a.m.	24.0	U/H
			2	1:50 p.m.	2.4	
			3	2:29 p.m.	24.0	U/H
			4	5:49 p.m.	24.0	U/H
8.	84	6	1	8:30 a.m.	24.0	U/H
			2	10:05 a.m.	24.0	U/H
			3	10:50 p.m.	24.0	U/H
			4	3:50 p.m.	4.0	U
			5	4:20 p.m.	7.2	U
			6	6:00 p.m.	0.8	U
9.	112	4	1	6:30 a.m.	64.0	U/H/U
			2	14:23 p.m.	40.0	U/H/U
			3	15:51 p.m.	0.8	U
			4	16:08	7.2	U
10.	144	3	1	6:30 a.m.	64.0	U/H/U
			2	14:23 a.m.	16.0	U/H
			3	16:15 p.m.	64.0	U/H/U
11.	240	5	1	6:30 a.m.	1.2	U
			2	9:32 a.m.	240.0	U/H/U
			3	13:17 p.m.	2.4	U
			4	13:56 p.m.	0.8	U
			5	14:33 p.m.	24.0	U/H
12.	524	3	1	11:30 a.m.	4.0	U
			2	11:45 a.m.	400.0	U/H/U
			3	19:00 p.m.	120.0	U/H/U

U refers to EPA Urban
H refers to EPA Highway

Twenty-four-hour Driving Cycle for the Variable-Route Delivery Van

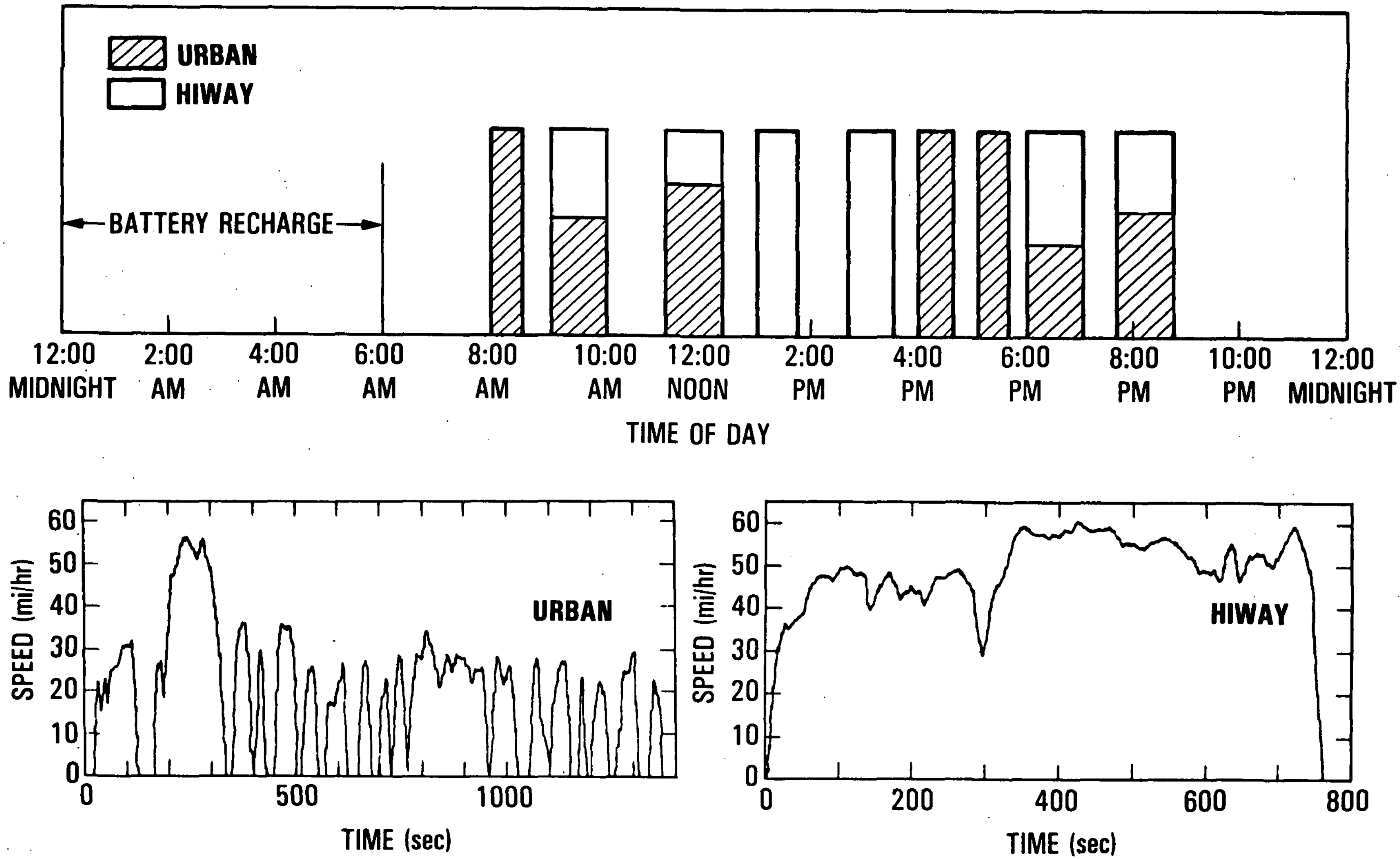
	Daily Distances, km	Time	Trip Length, km	EPA Cycle
1.	12	8:30 am	6	U Partial
		4:30 pm	6	
2.	24	8:30 am	12	U
		4:30 pm	12	U
3.	36	9:00 am	12	U
		1:00 pm	12	U
		4:30 pm	12	U
4.	48	9:00 am	12	U
		10:30 am	12	U
		1:30 pm	12	U
		4:30	12	U
5.	60	8:30 am	12	U
		10:45 am	12	U
		1:30 pm	12	U
		3:30 pm	12	U
		5:00 pm	12	U
6.	92	8:30 am	28	U/H
		12:00 pm	28	U/H
		2:00 pm	12	U
		3:30 pm	12	U
		5:00 pm	12	U
7.	120 km	7:30 am	28	U/H
		10:30 am	28	U/H
		11:30 am	40	U/H/U
		4:30 pm	24	U
8.	152 km	7:30 am	44	U/H/U
		10:30 am	44	U/H/U
		12:30 pm	28	U/H
		2:30 pm	28	U/H
		5:00 pm	12	U
9.	192 km	7:30 am	72	U/3H/U
		1:30 pm	72	U/3H/U
		3:30 pm	24	U
		5:30 pm	24	U

U refers to EPA Urban
H refers to EPA Highway

Twenty-four-hour Driving Cycle for the 60-km Fixed-Route Delivery Van

Time	Trip Length, km	Cycle
8:30	12	U
10:00	12	U
12:00	12	U
1:30	12	U
3:30	12	U
The daily driving schedule for the 100 km (daily travel) is:		
8:30	12	U
9:30	16	H
10:30	12	U
11:30	12	U
1:30	16	H
2:30	12	U
3:30	12	U
4:30	12	U

U refers to EPA Urban
H refers to EPA Highway



Typical Daily Schedule

APPENDIX C

This appendix presents the configuration and strategy study curves for all of the vehicles except the five-passenger one. The five-passenger vehicle curves were surveyed in Section V of the report. Figures C-1 through C-24 are the curves for the configuration study and Figures C-25 through C-40 are those for the strategy study. The results are summarized in Tables C-1 and C-2.

For the commuter vehicle, the series/parallel hybrid configuration has the greatest petroleum savings, very similar to those of an electric-only vehicle. The series hybrid is somewhat better than the rear motor parallel, but not by a significant margin. The front motor parallel has the lowest petroleum savings of the the four configurations.

The results are different for the four-passenger vehicle. The series/ parallel remains the best configuration, and the rear motor parallel is a strong second choice. The series and the front motor parallel configurations have nearly identical petroleum savings and would be third alternatives.

For the two vans, the rear motor parallel and the series/parallel have comparable petroleum savings while the front motor parallel is preferable to the series. These results are for the 90th percentile annual distance. At the 60th percentile distance, the fixed-route van uses little or no fuel and, therefore, the configuration is not important. In this case, the vehicle should be an electric.

The strategy study results are clearly reveal that the peaking strategy is the best one for all vehicles and the sharing strategy is the poorest one under all conditions. The margin between the peaking and the either/or strategies changes somewhat with different configurations, but the results still very much favor use of the peaking strategy.

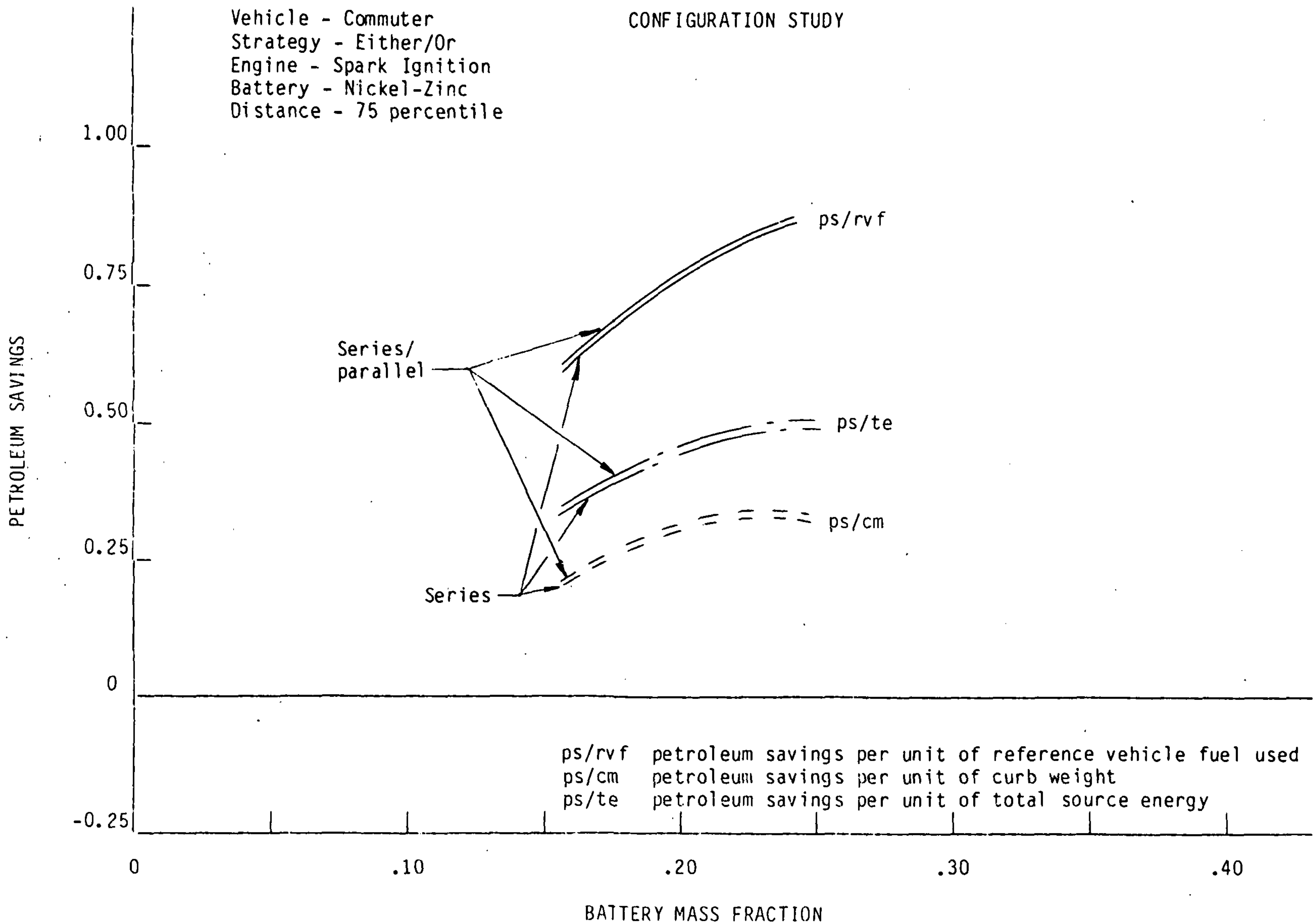


Figure C-1. Petroleum Savings for Commuter Vehicle Using Either/Or Strategy

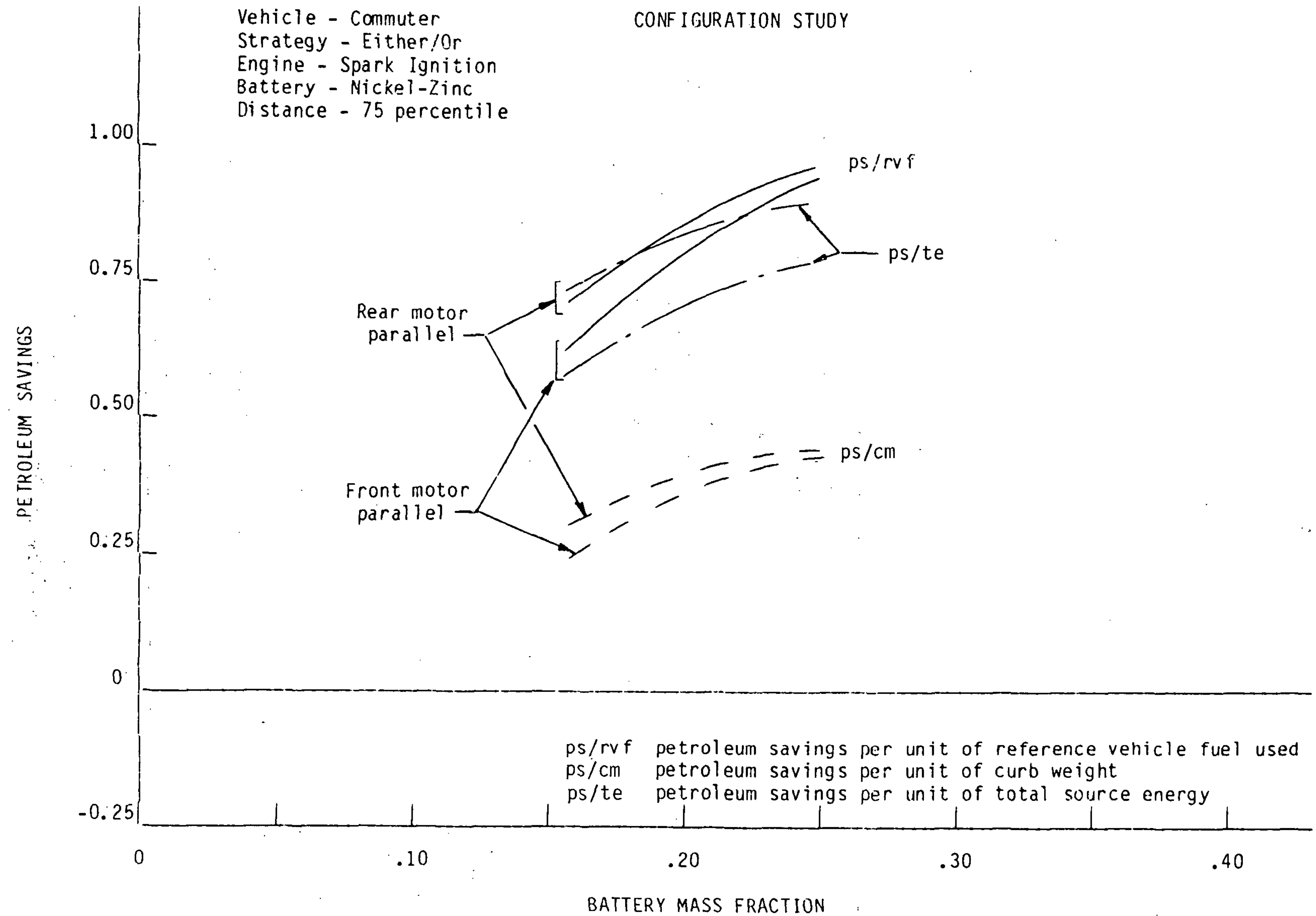


Figure C-2. Petroleum Savings for Commuter Vehicle Using Either/Or Strategy

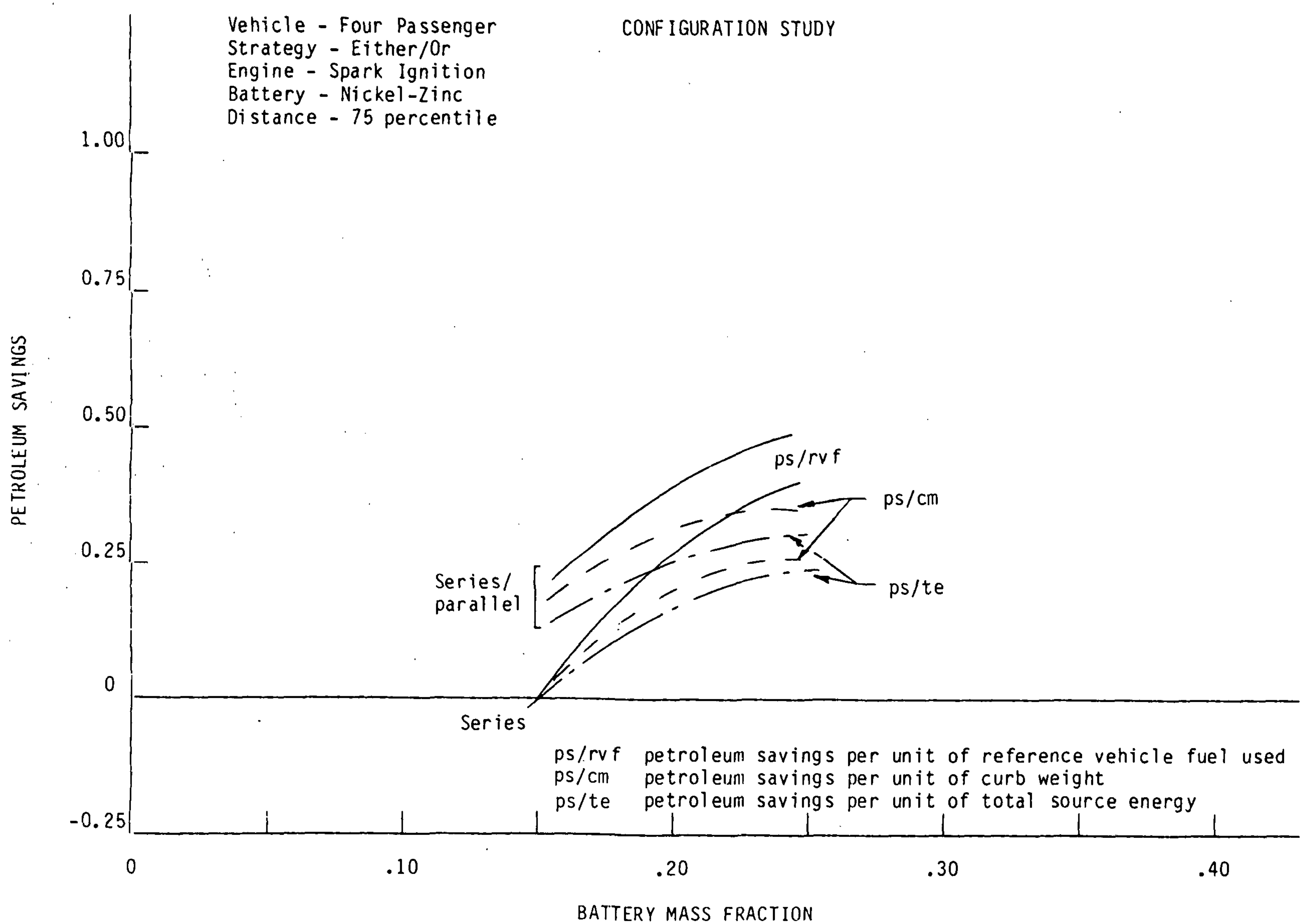


Figure C-3. Petroleum Savings for Four-Passenger Vehicle Using Either/Or Strategy

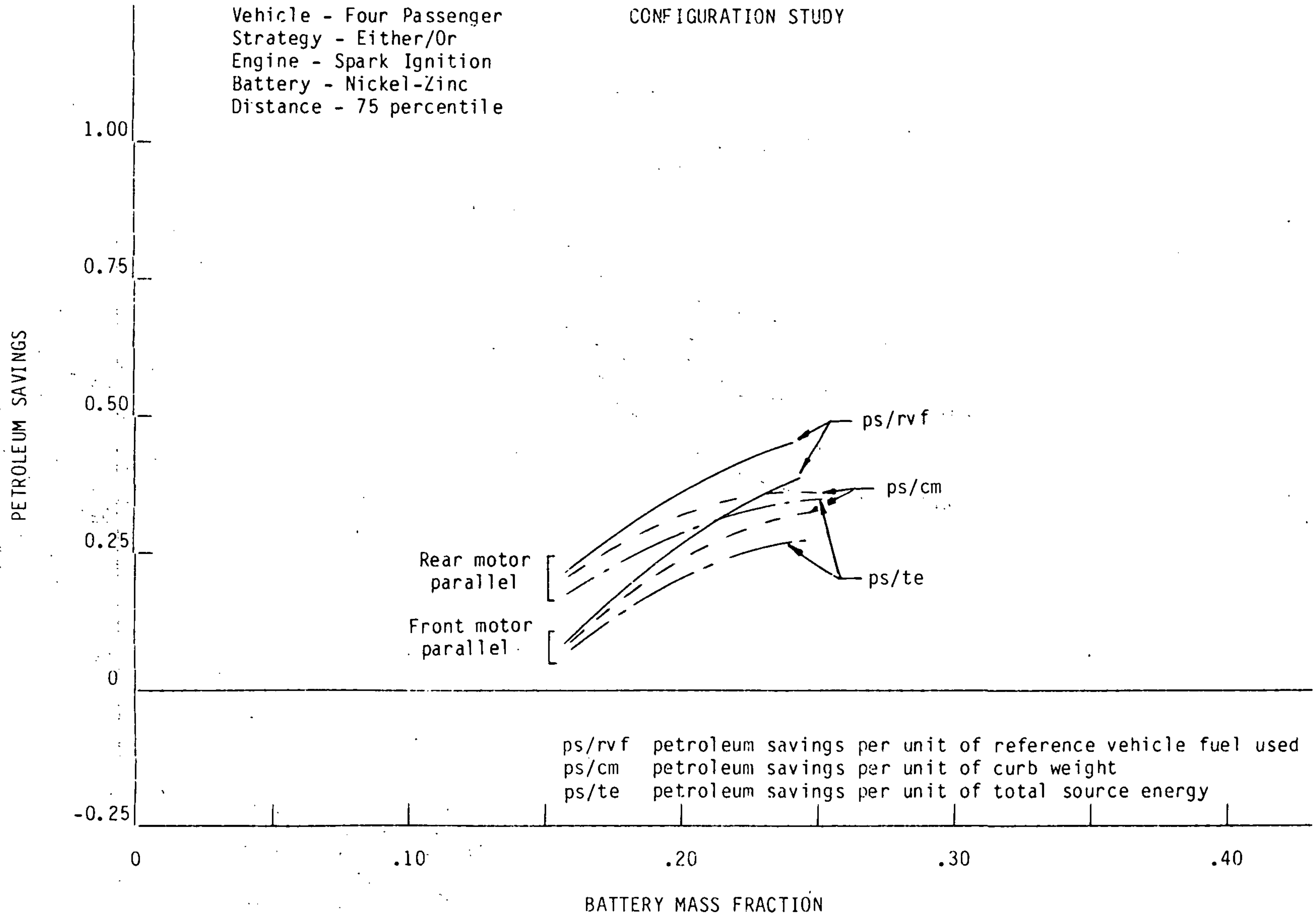


Figure C-4. Petroleum Savings for Four-Passenger Vehicle Using Either/Or Strategy

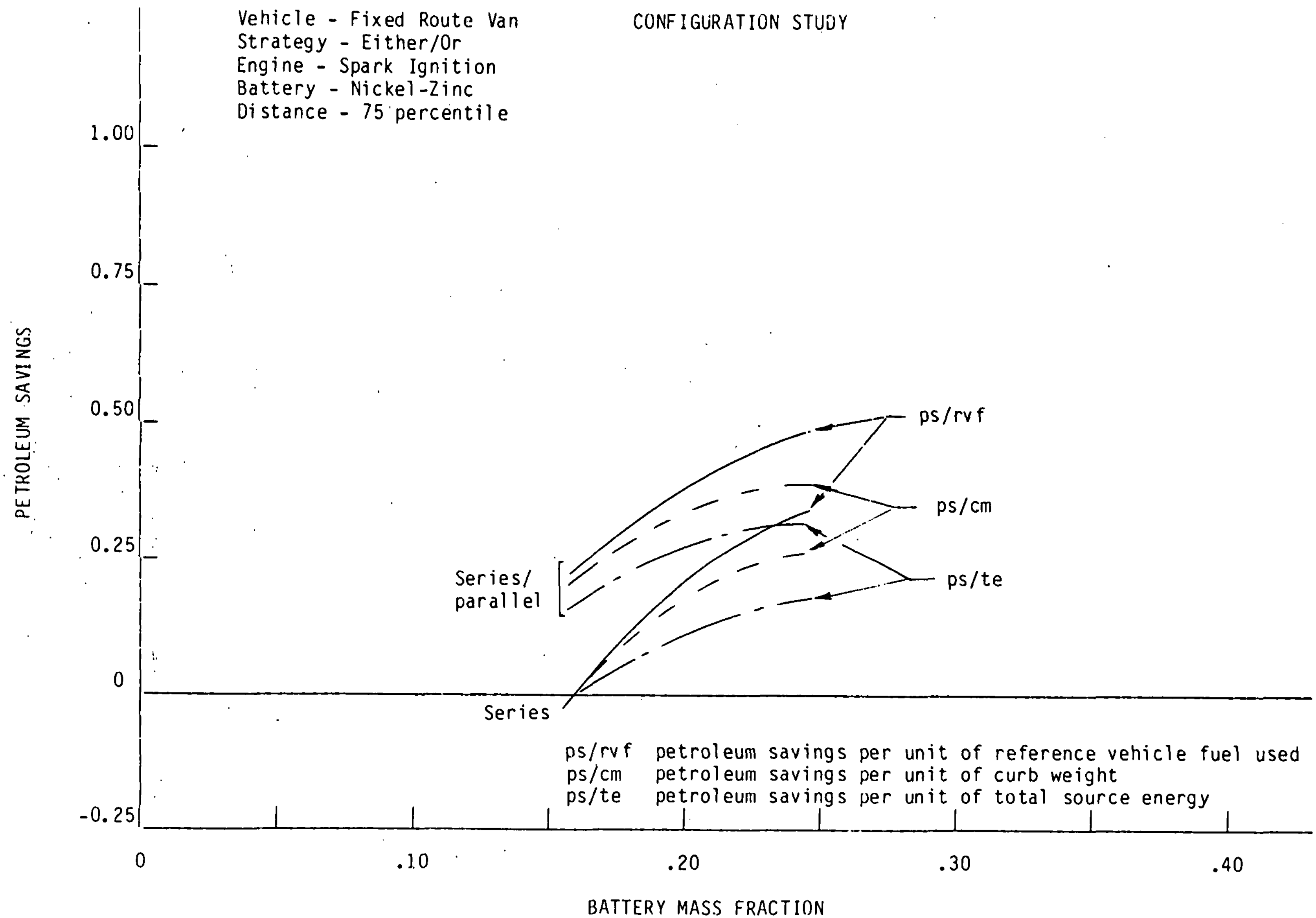


Figure C-5. Petroleum Savings for Fixed-Route Van Using Either/Or Strategy

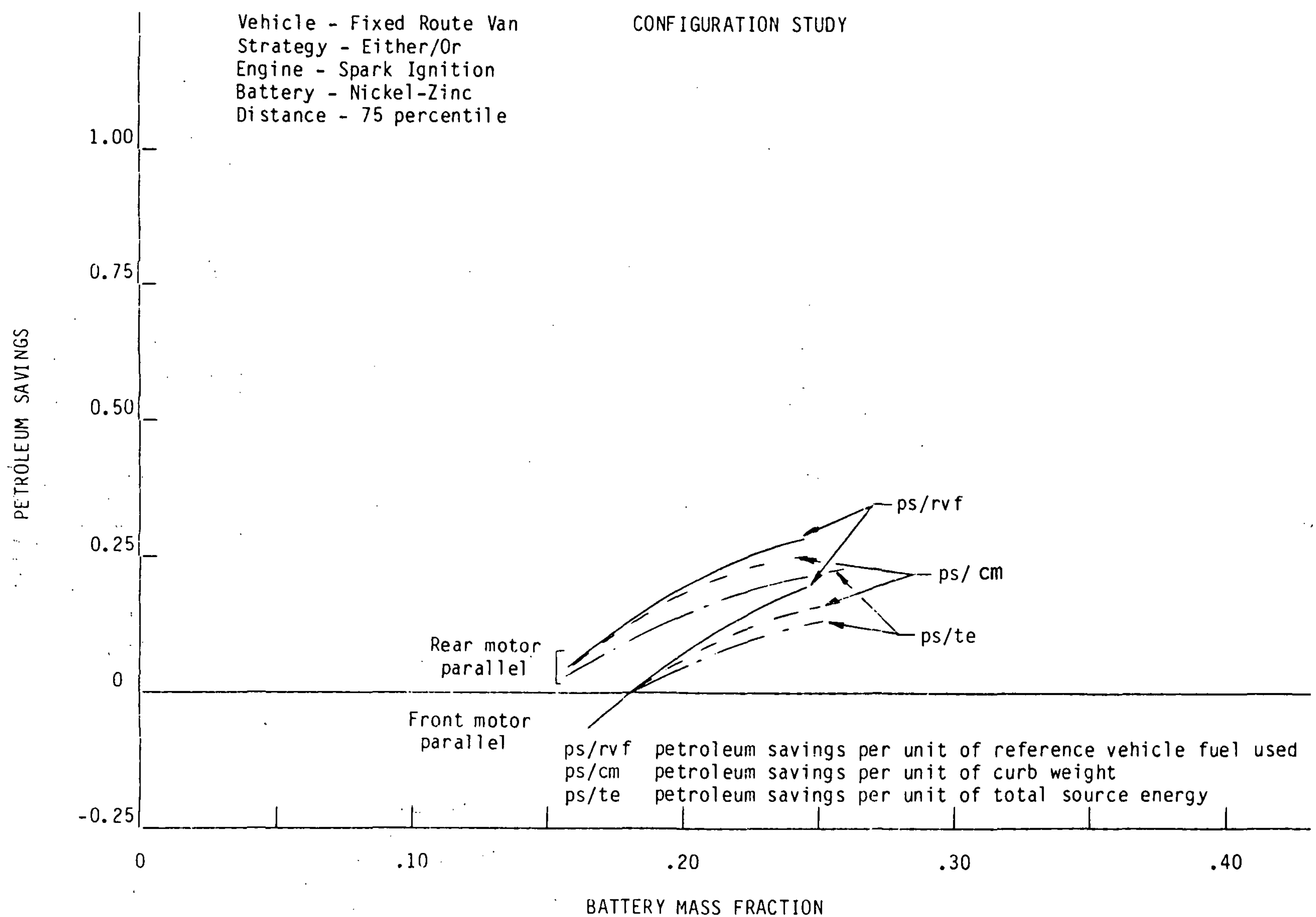


Figure C-6. Petroleum Savings for Fixed-Route Van Using Either/Or Strategy

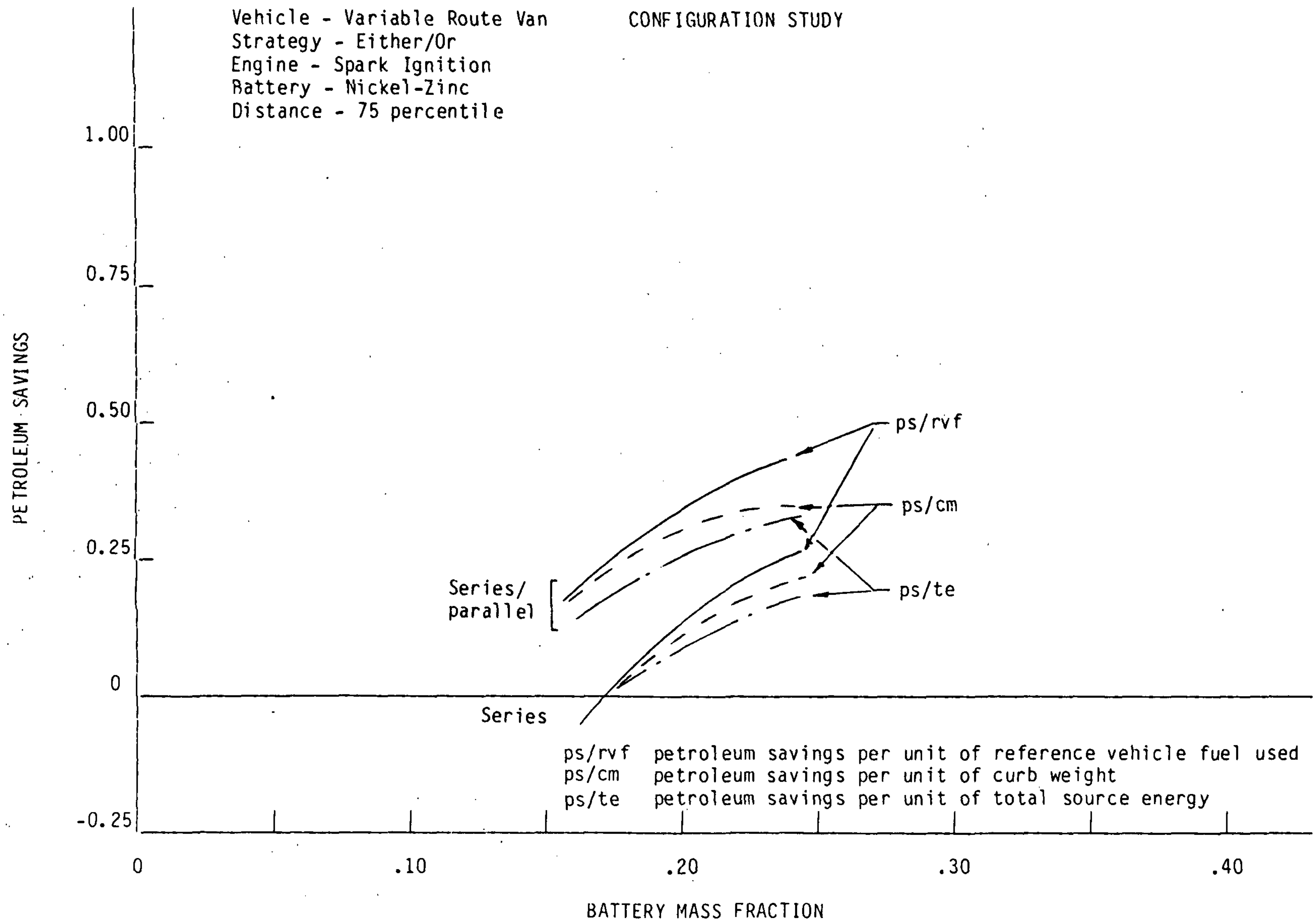


Figure C-7. Petroleum Savings for Variable-Route Van Using Either/Or Strategy

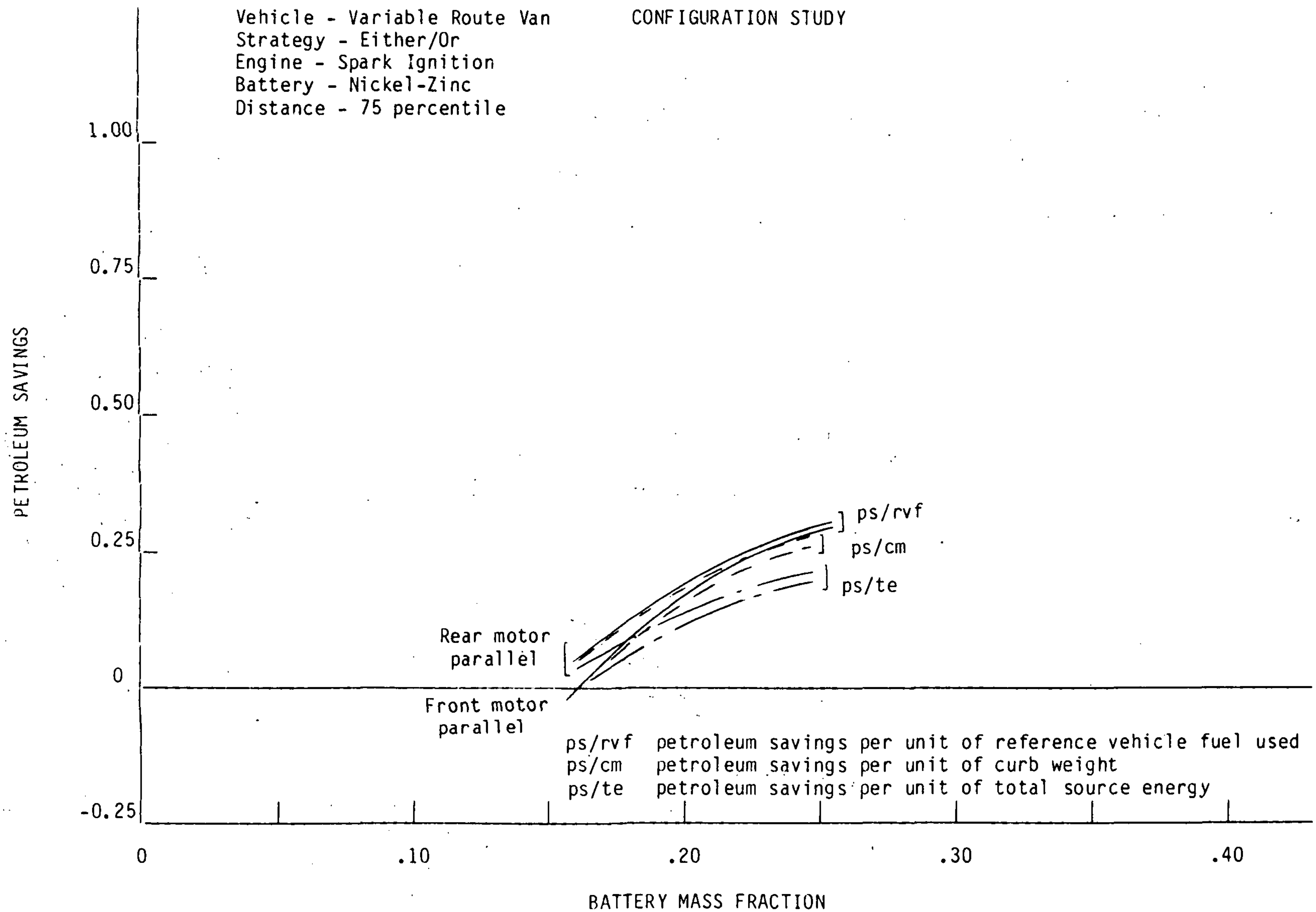


Figure C-8. Petroleum Savings for Variable-Route Van Using Either/Or Strategy

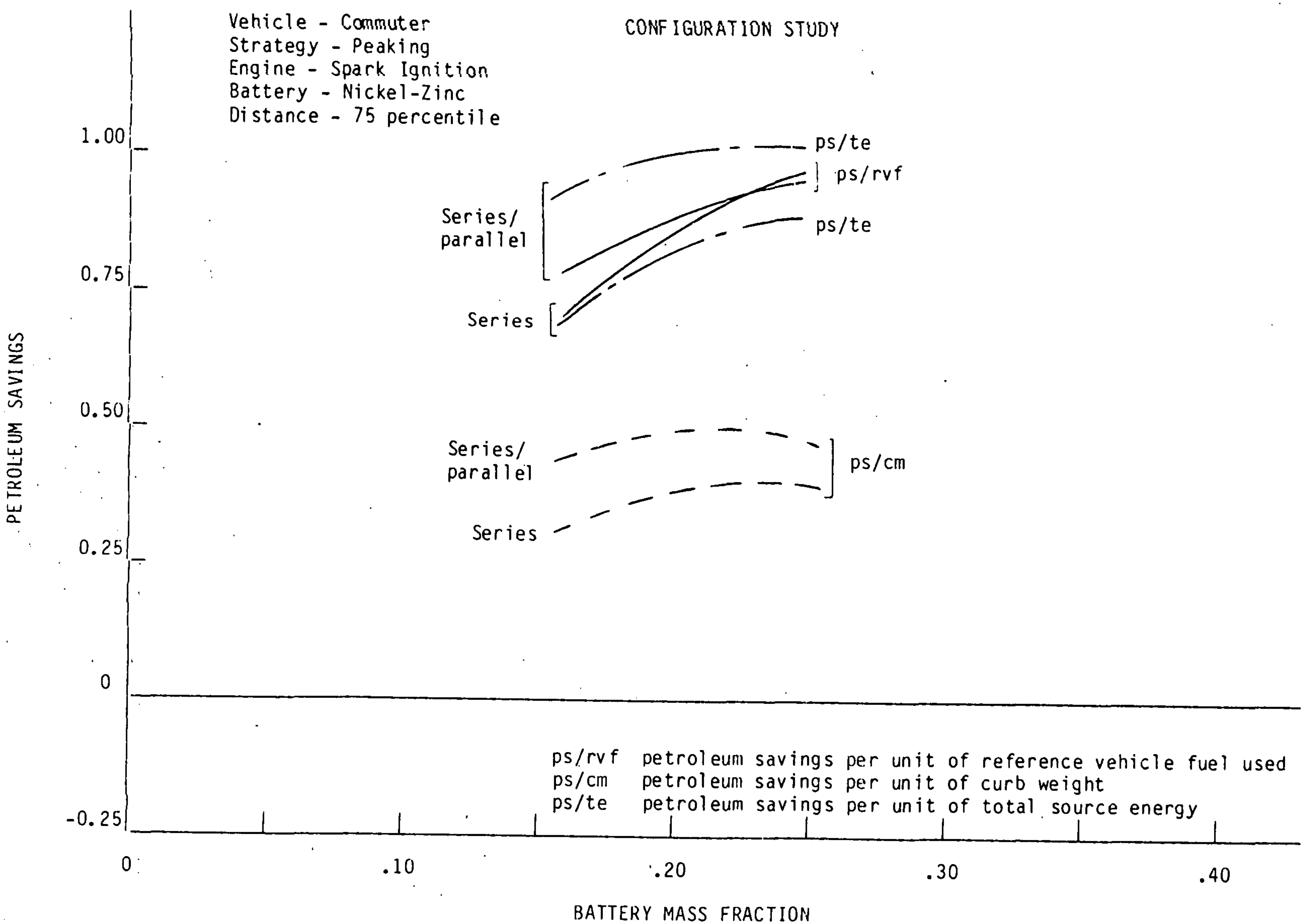


Figure C-9. Petroleum Savings for Commuter Vehicle Using Peaking Strategy

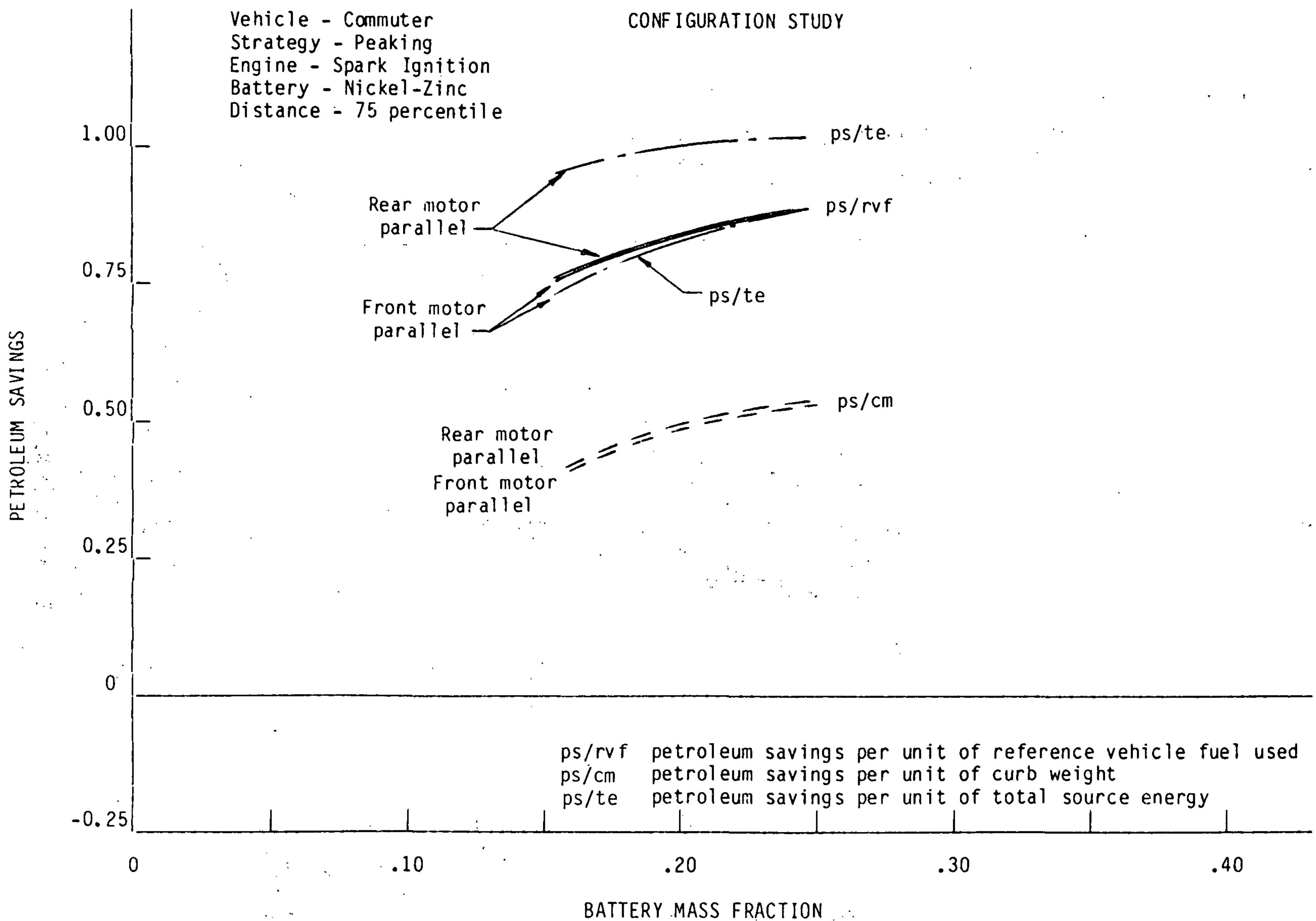


Figure C-10. Petroleum Savings for Commuter Vehicle Using Peaking Strategy

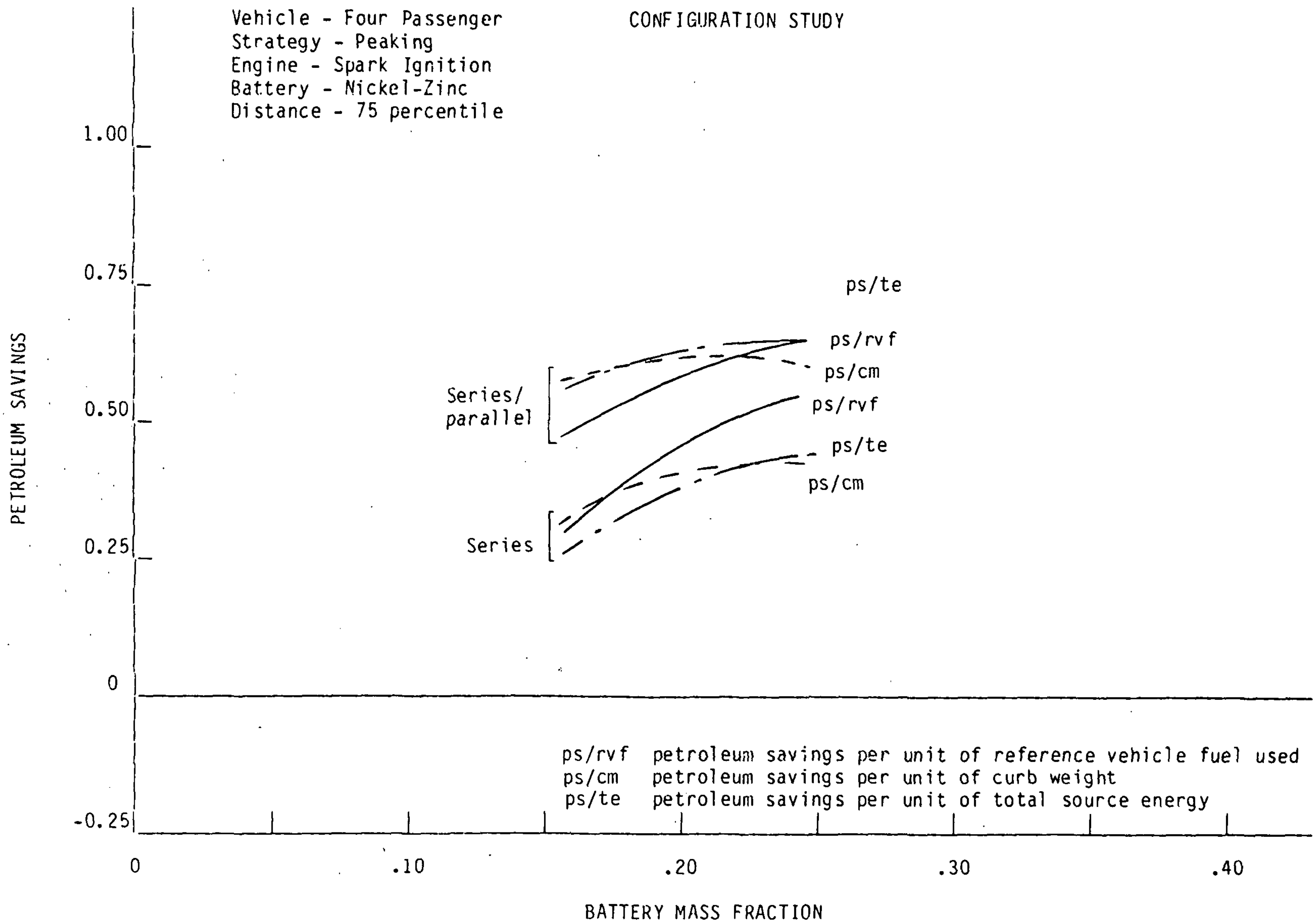


Figure C-11. Petroleum Savings for Four-Passenger Vehicle Using Peaking Strategy

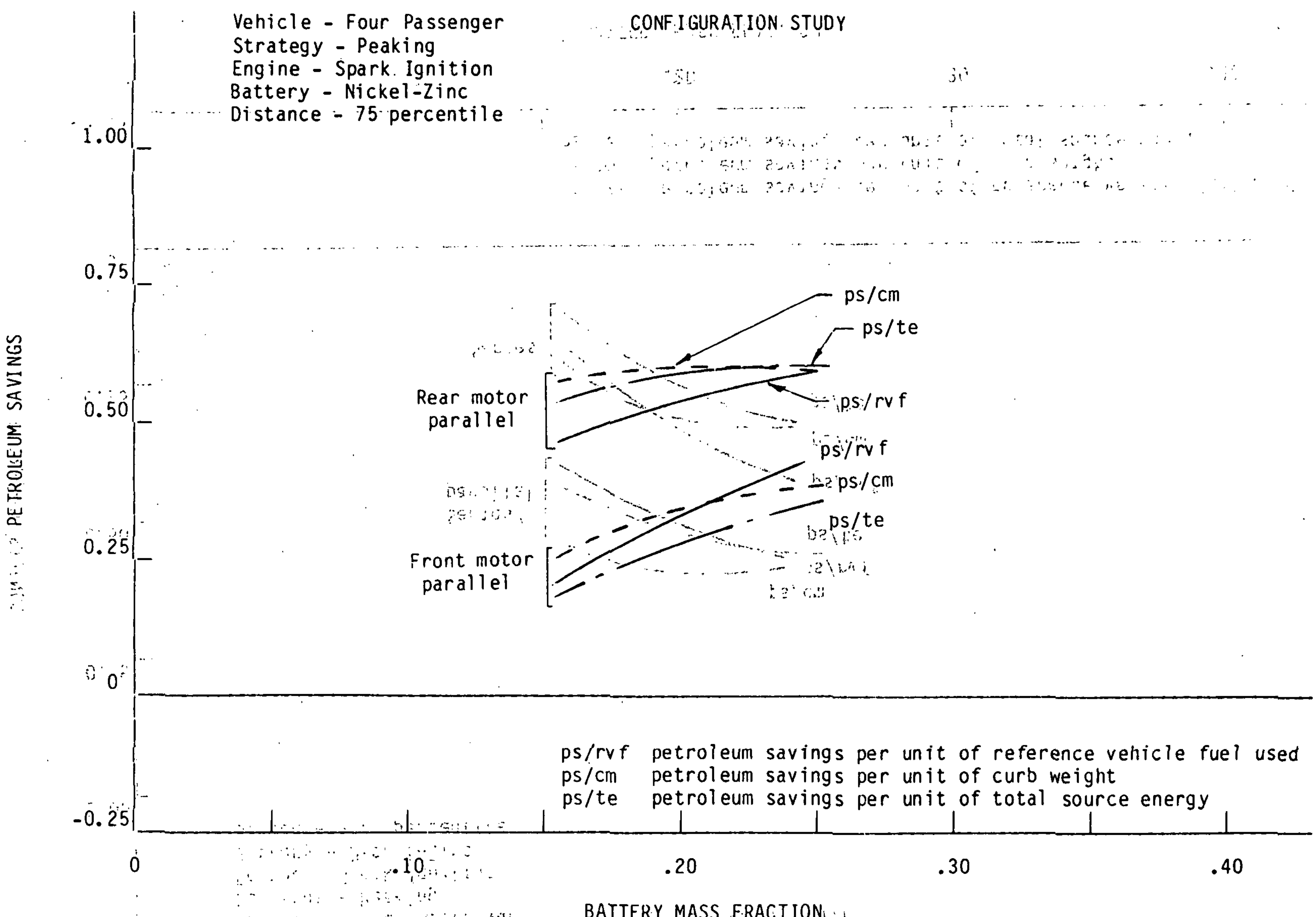


Figure C-12. Petroleum Savings for Four-Passenger Vehicle Using Peaking Strategy

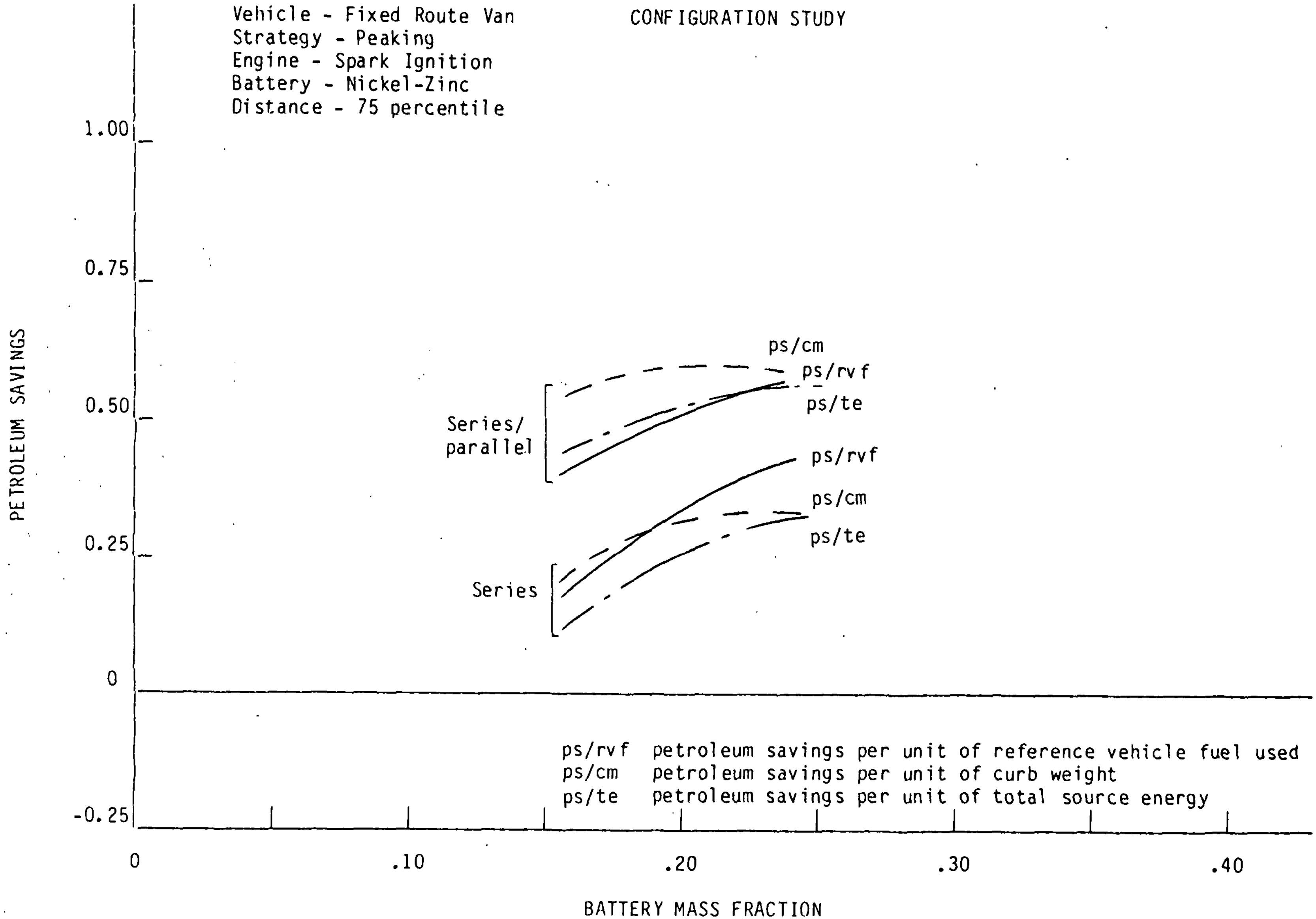


Figure C-13. Petroleum Savings for Fixed-Route Van Using Peaking Strategy

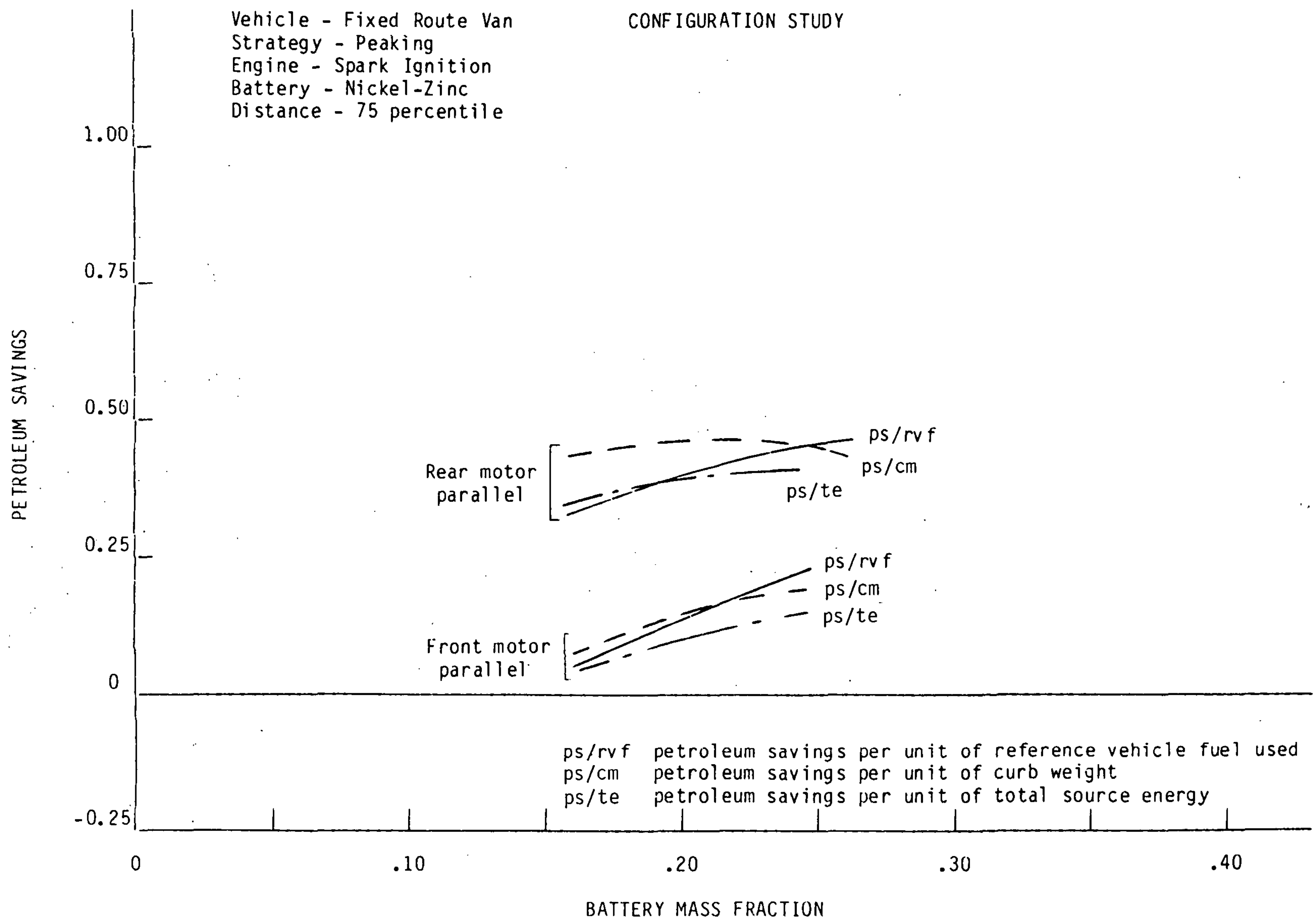


Figure C-14. Petroleum Savings for Fixed-Route Van Using Peaking Strategy

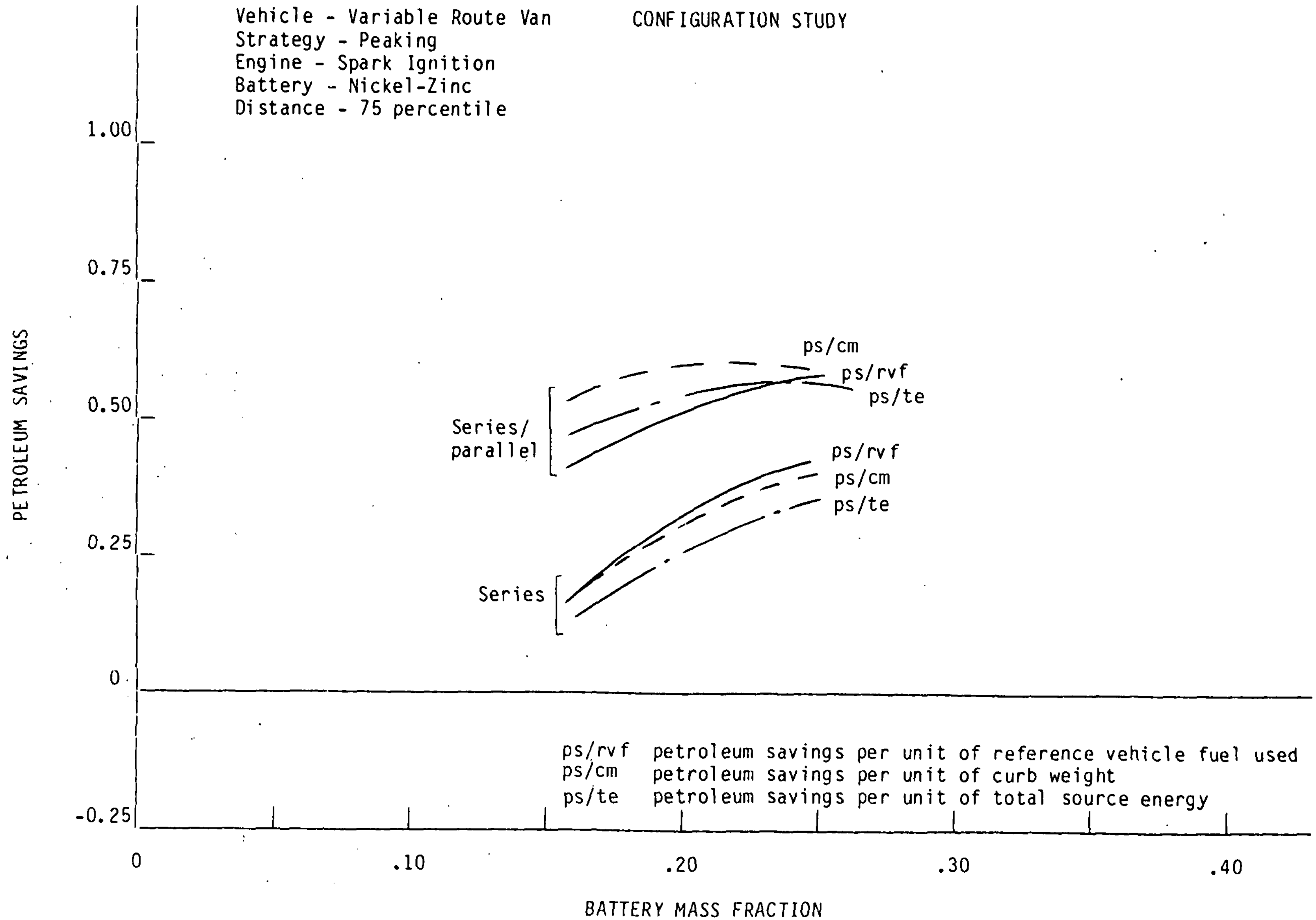


Figure C-15. Petroleum Savings for Variable-Route Van Using Peaking Strategy

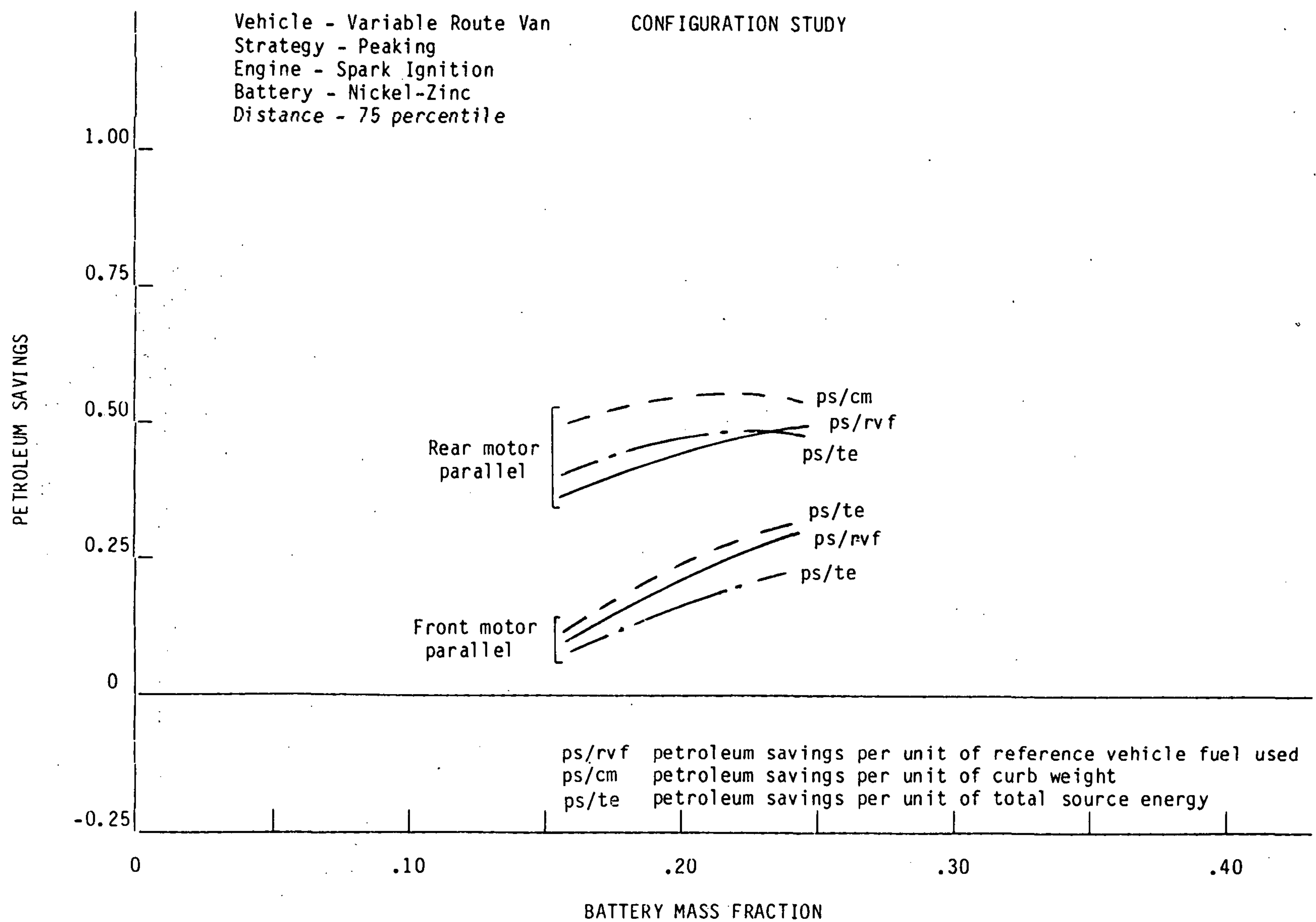


Figure C-16. Petroleum Savings for Variable-Route Van Using Peaking Strategy

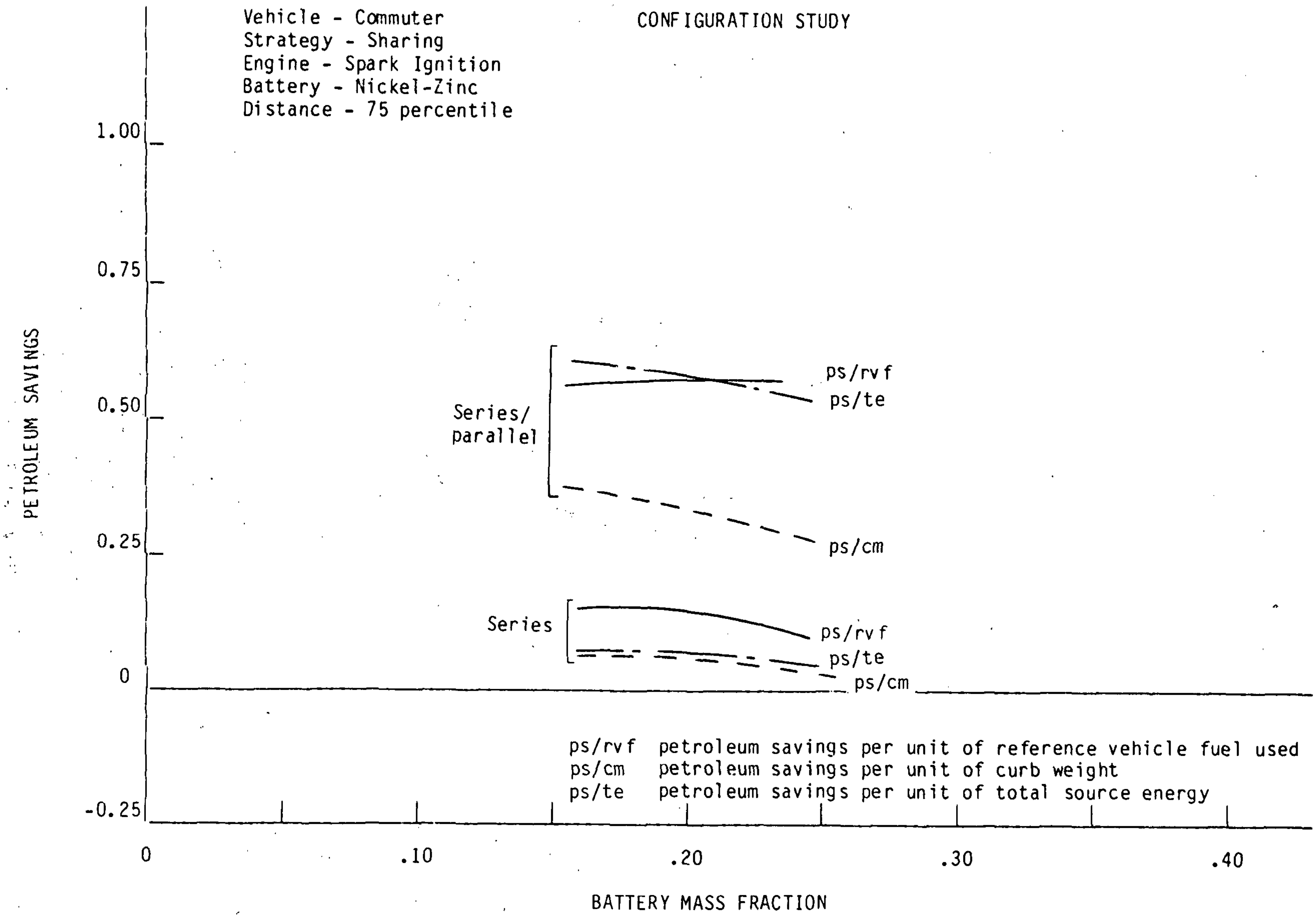


Figure C-17. Petroleum Savings for Commuter Vehicle Using Sharing Strategy

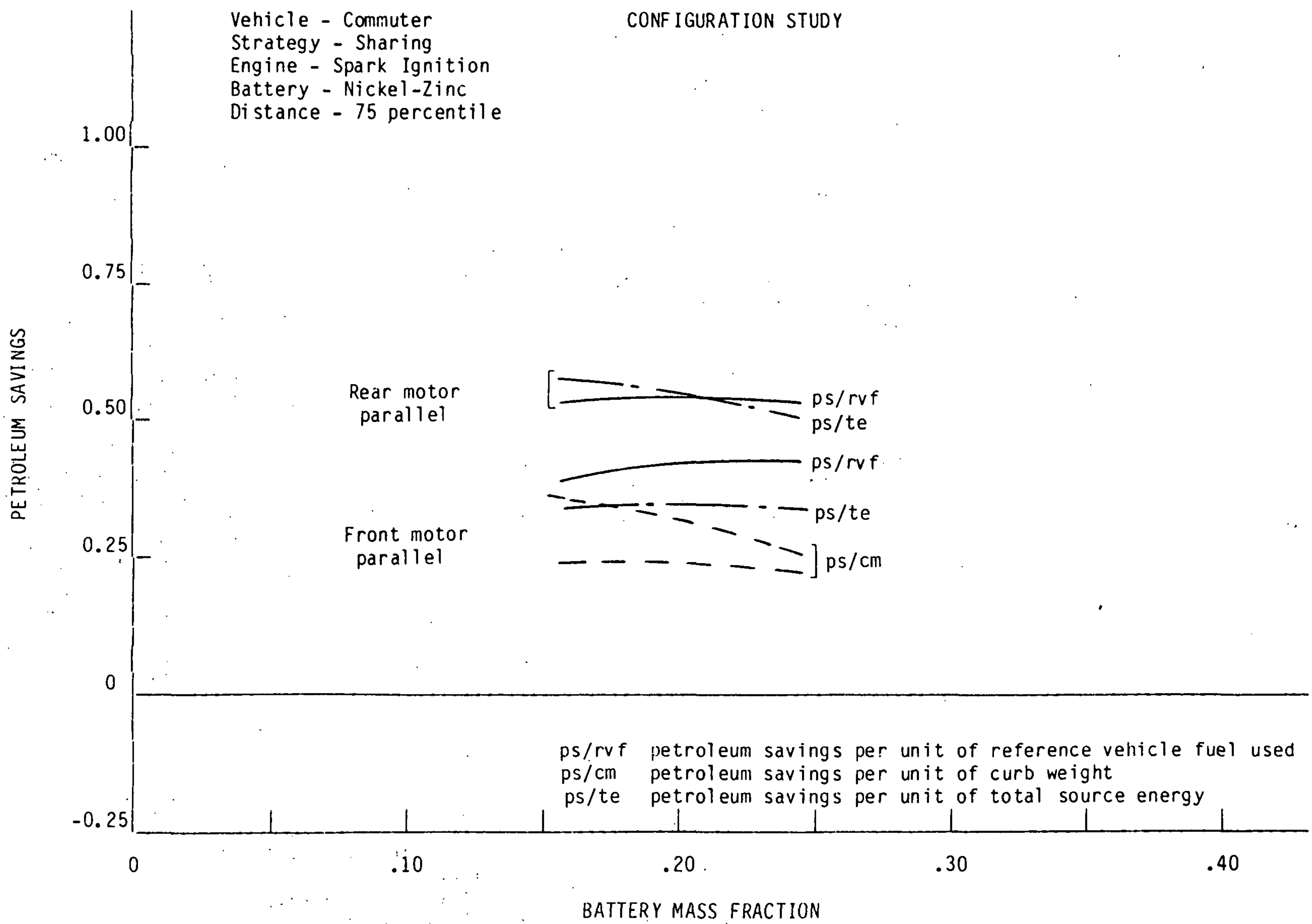


Figure C-18. Petroleum Savings for Commuter Vehicle Using Sharing Strategy

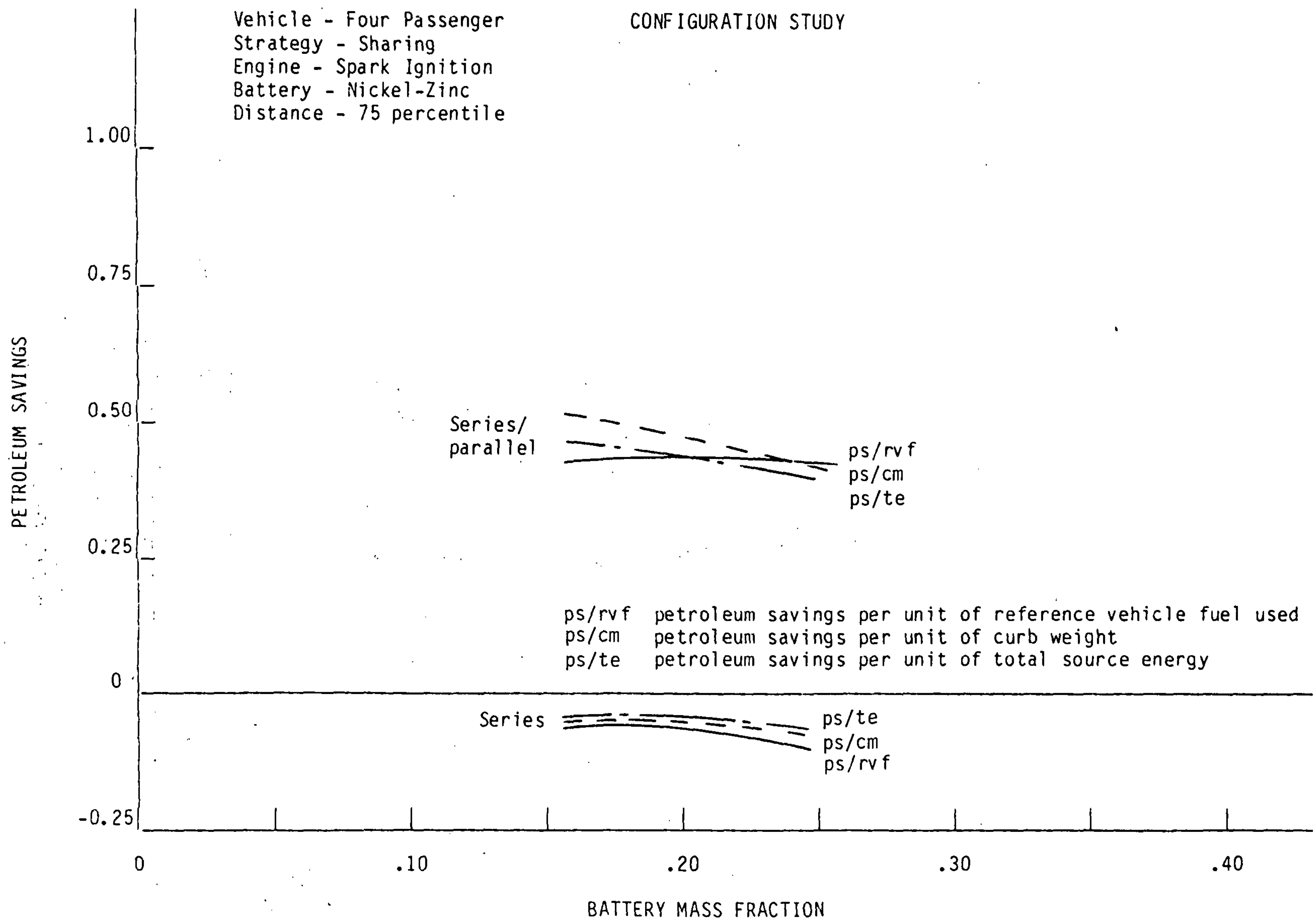


Figure C-19. Petroleum Savings for Four-Passenger Vehicle Using Sharing Strategy

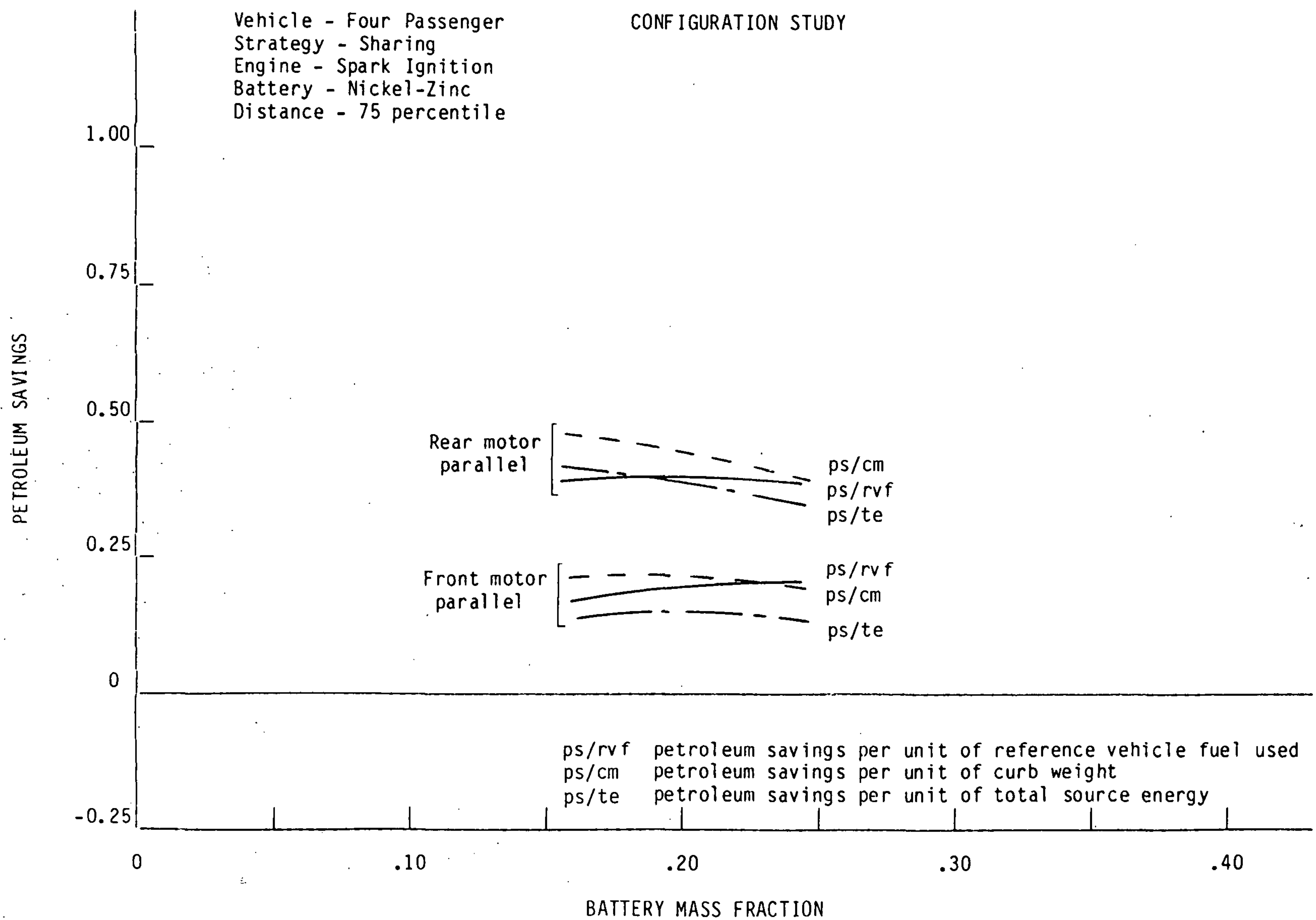


Figure C-20. Petroleum Savings for Four-Passenger Vehicle Using Sharing Strategy

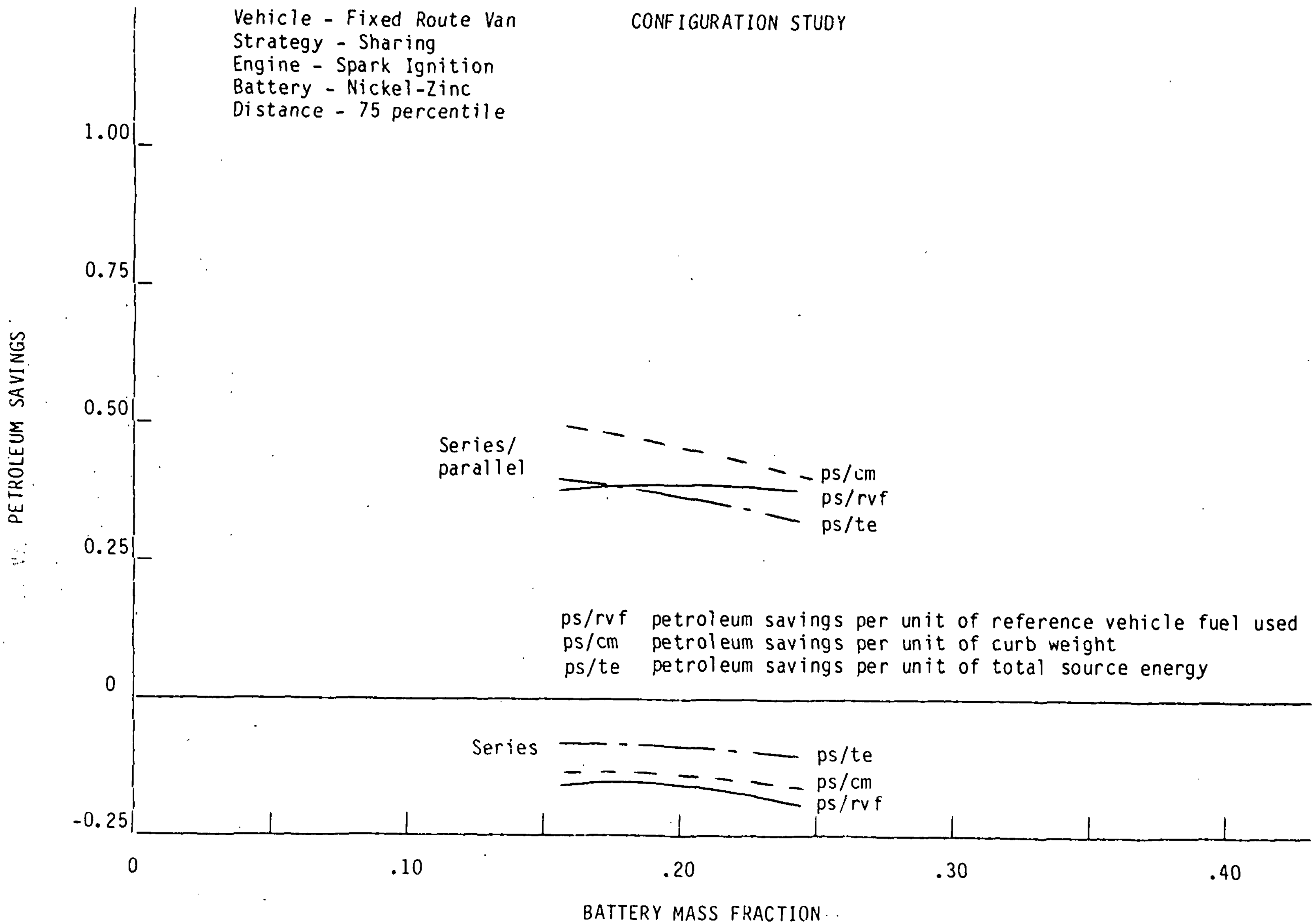


Figure C-21. Petroleum Savings for Fixed-Route Van Using Sharing Strategy

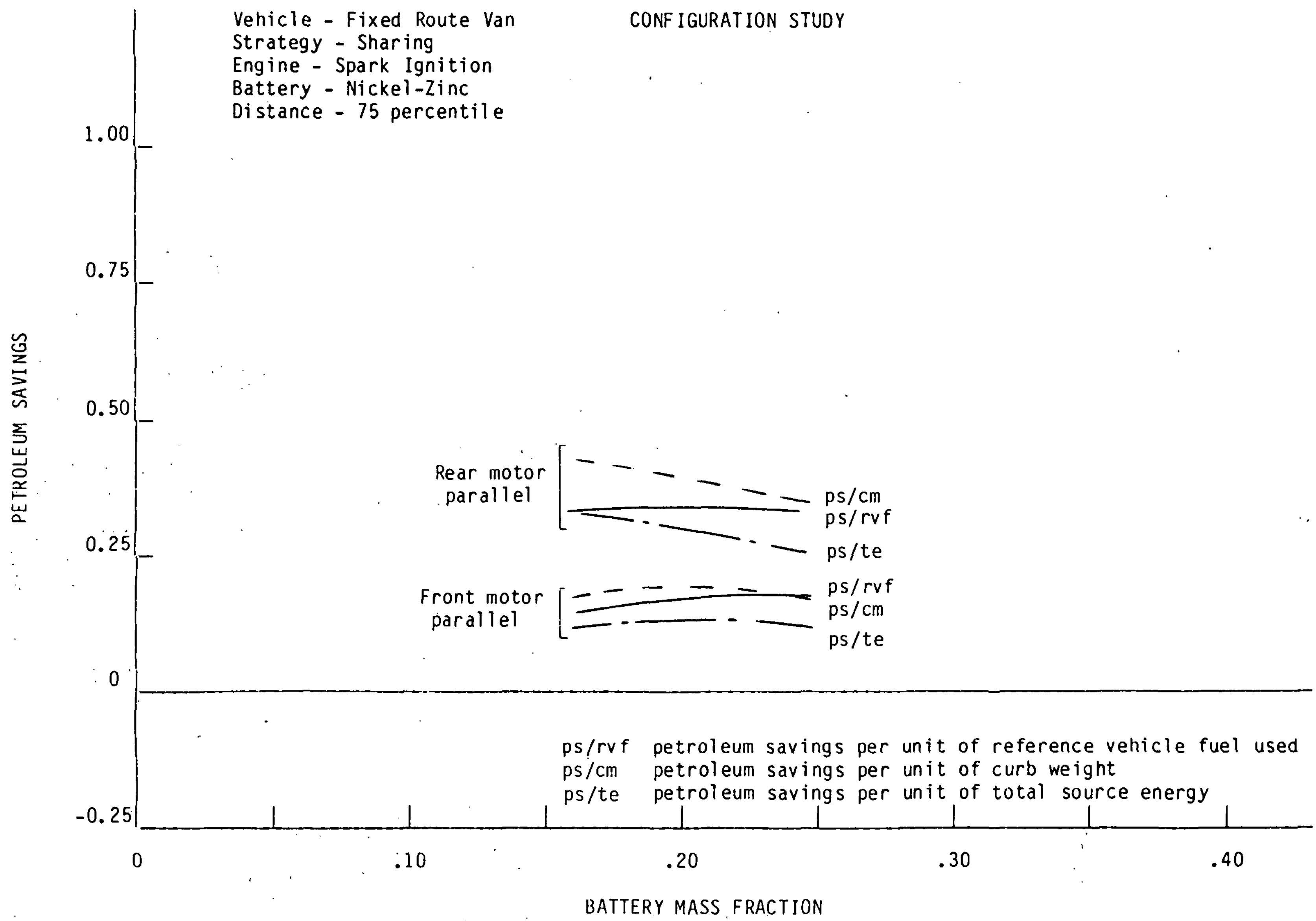


Figure C-22. Petroleum Savings for Fixed-Route Van Using Sharing Strategy

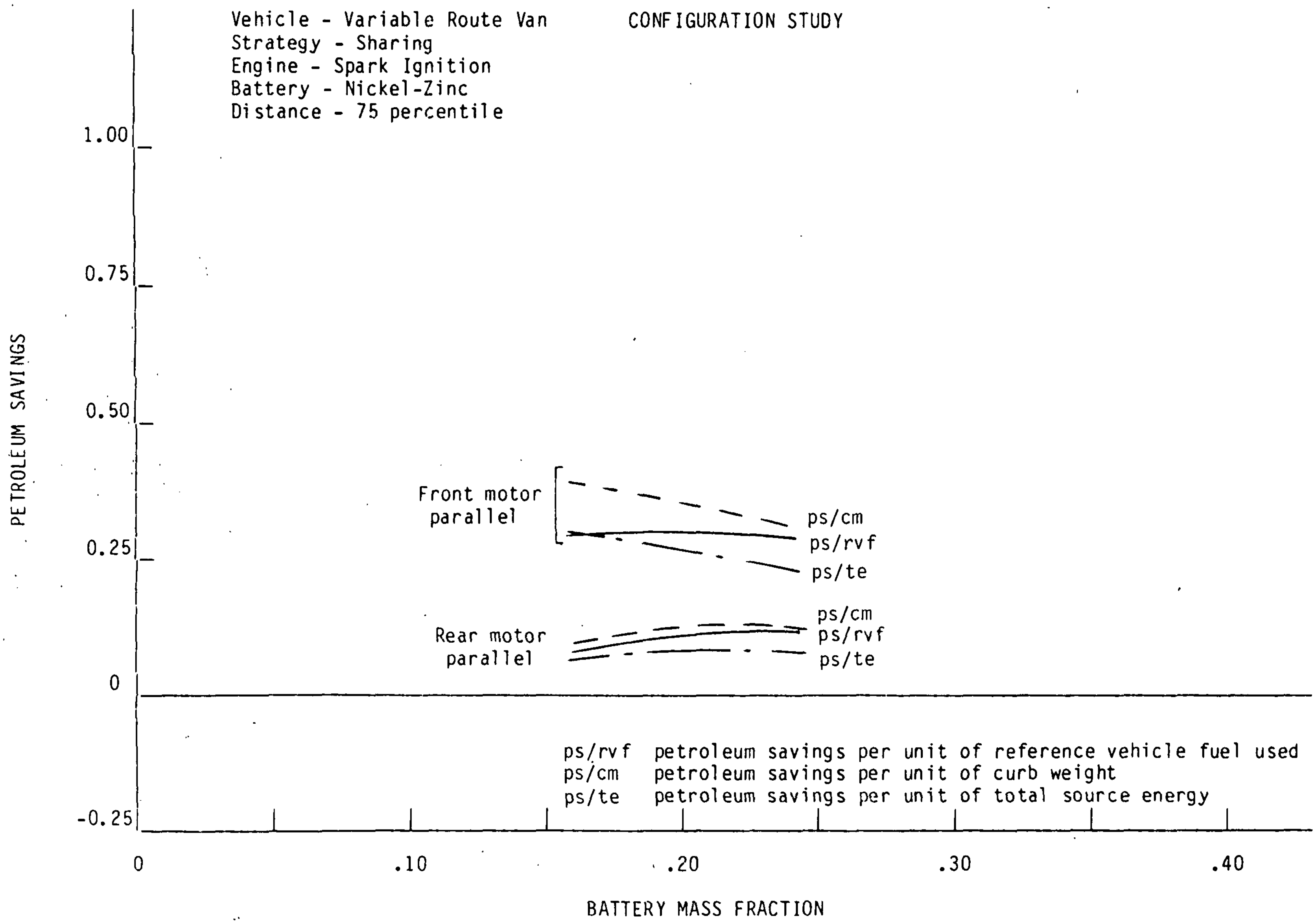


Figure C-23. Petroleum Savings for Variable-Route Van Using Sharing Strategy

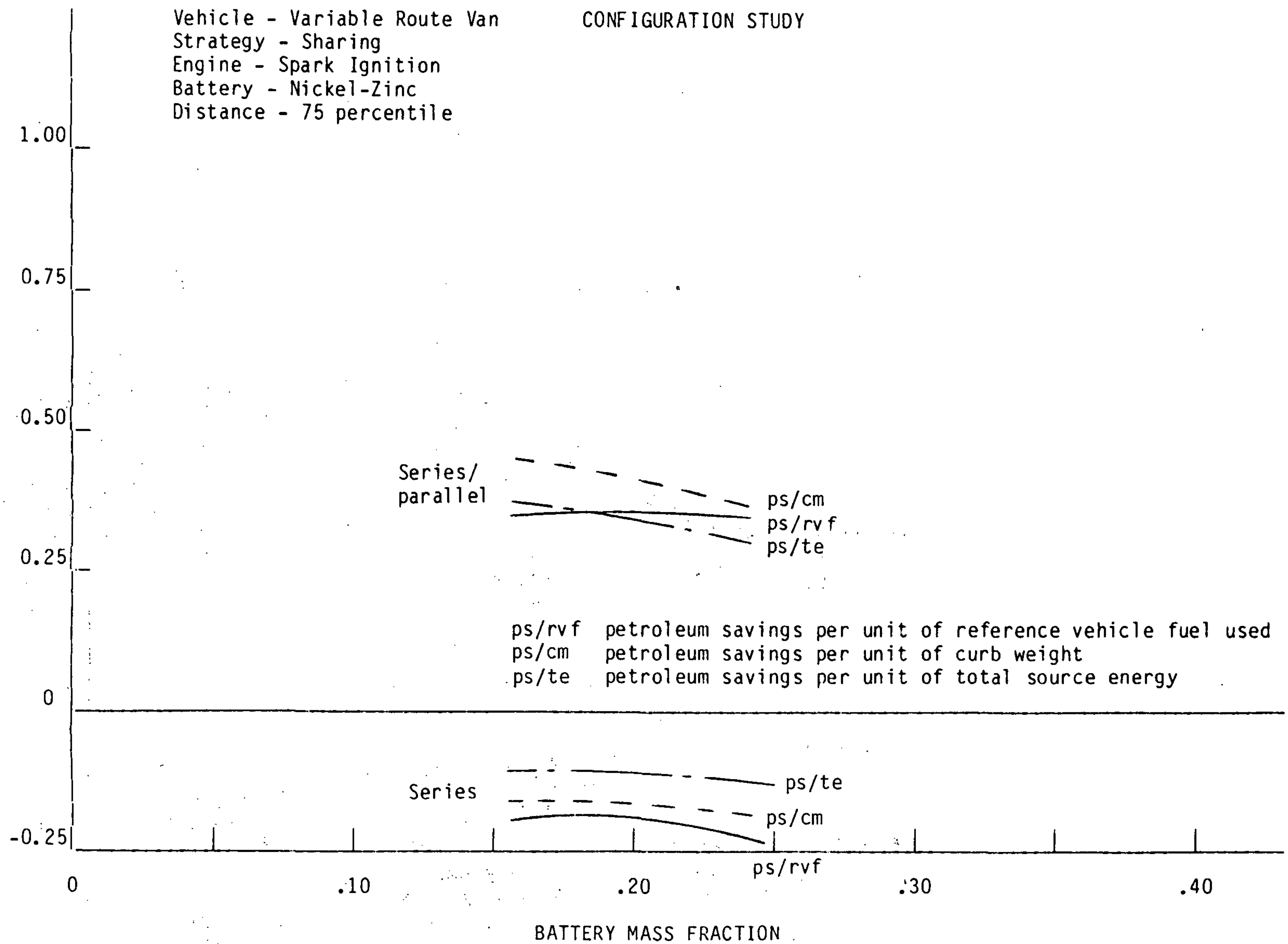


Figure C-24. Petroleum Savings for Variable-Route Van Using Sharing Strategy

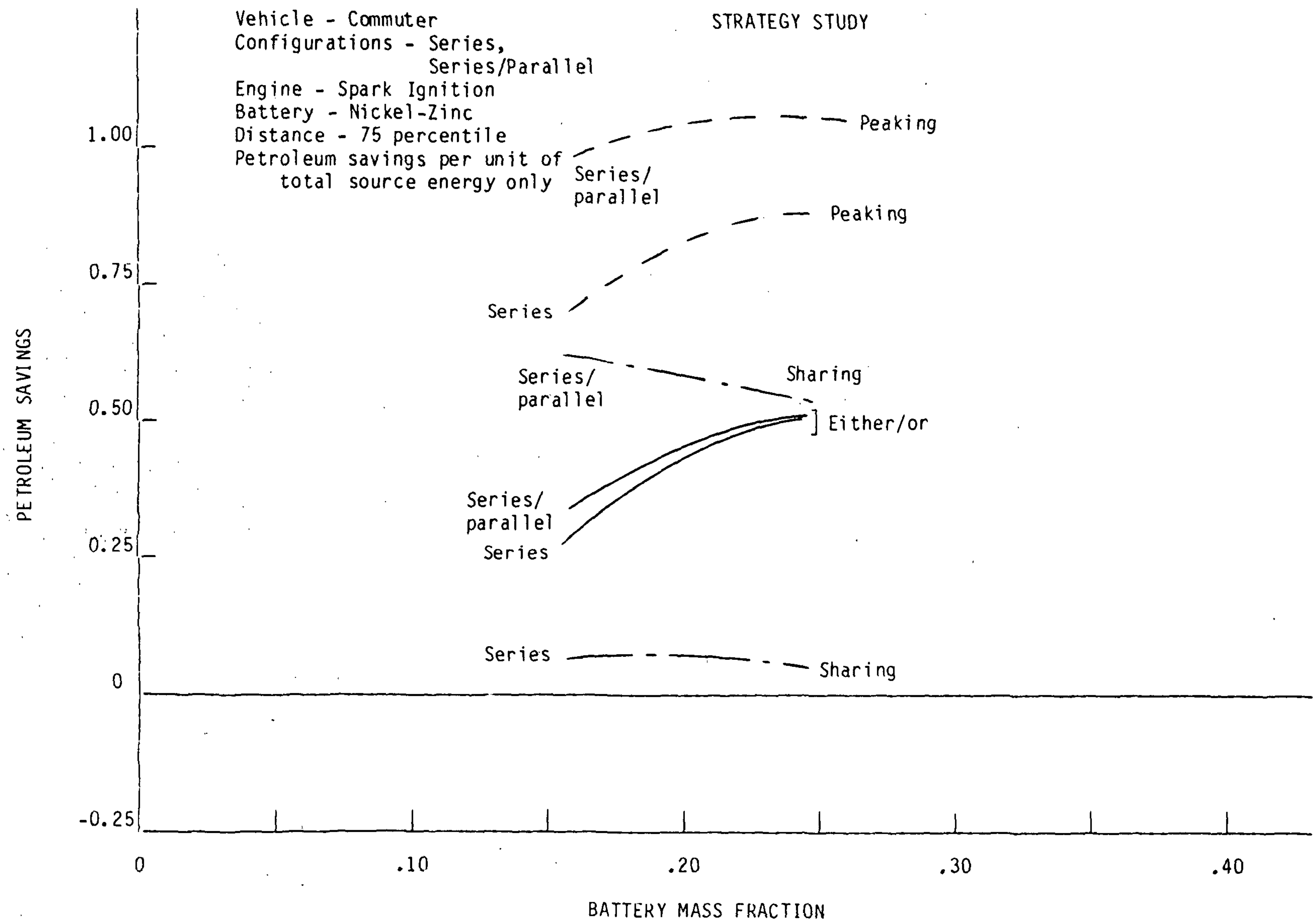


Figure C-25. Petroleum Savings for Commuter Vehicle with Series and Series/Parallel Configurations

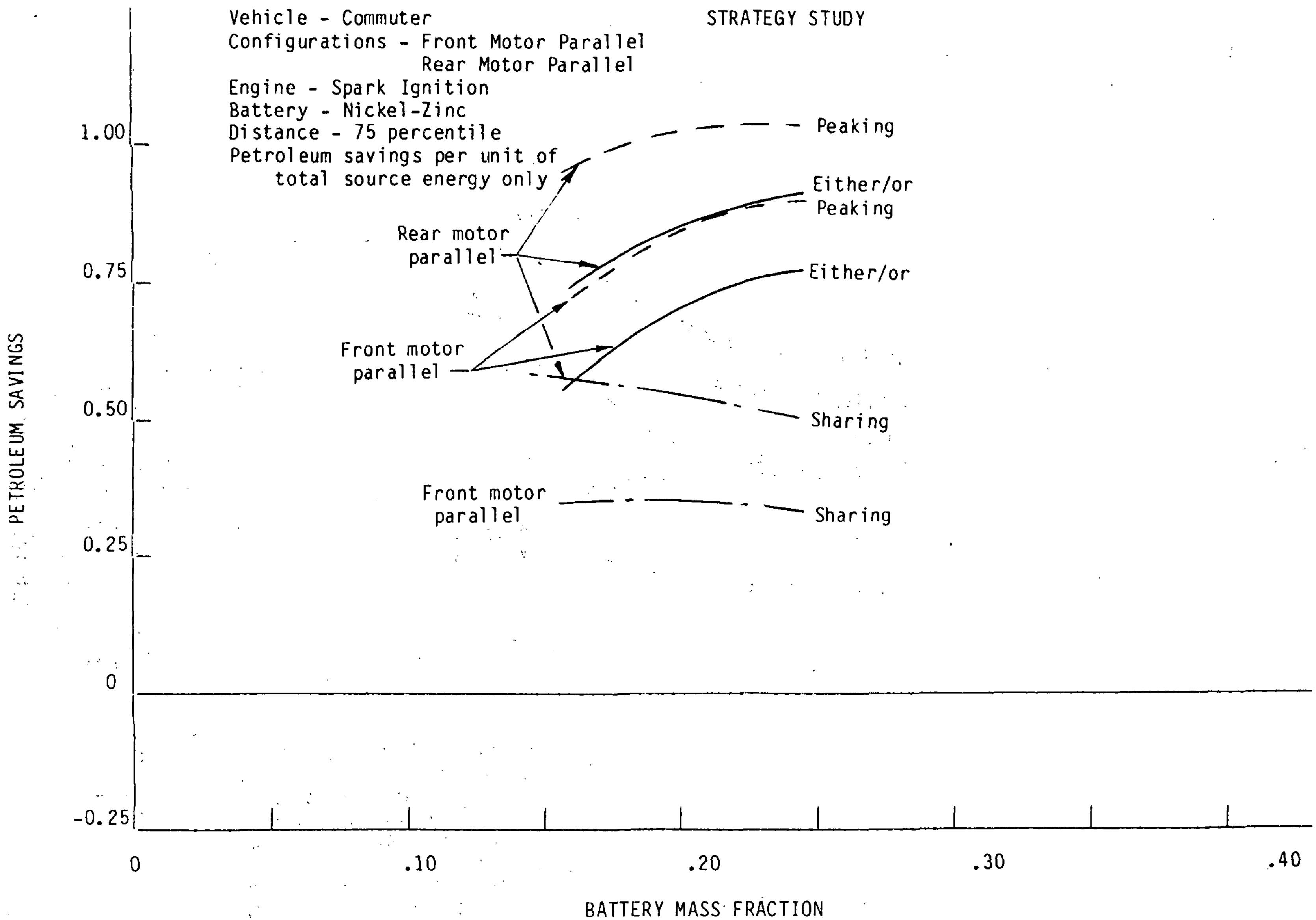


Figure C-26. Petroleum Savings for Commuter Vehicle with Front-Motor and Rear-Motor Parallel Configurations

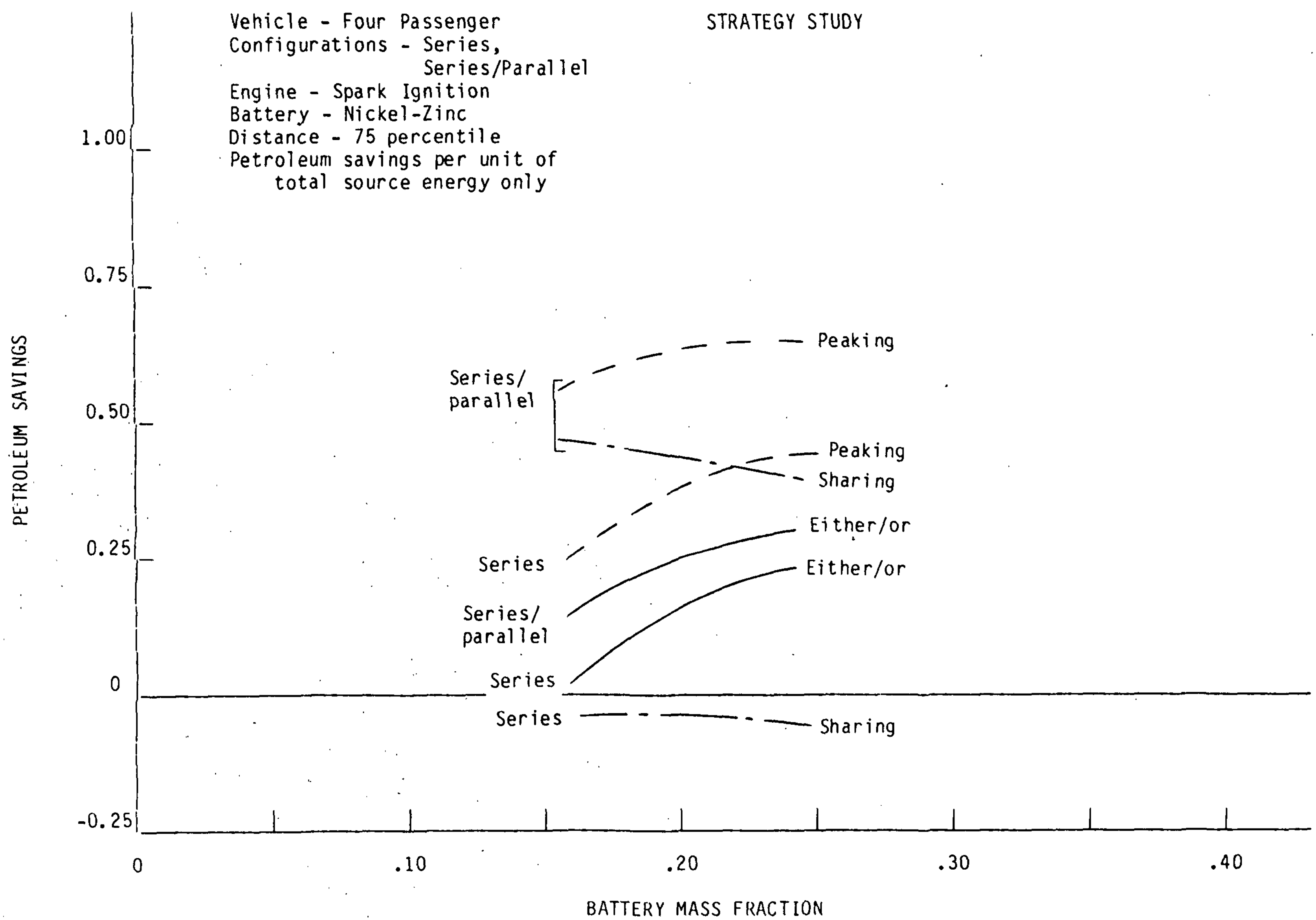


Figure C-27. Petroleum Savings for Four-Passenger Vehicle with Series and Series/Parallel Configurations

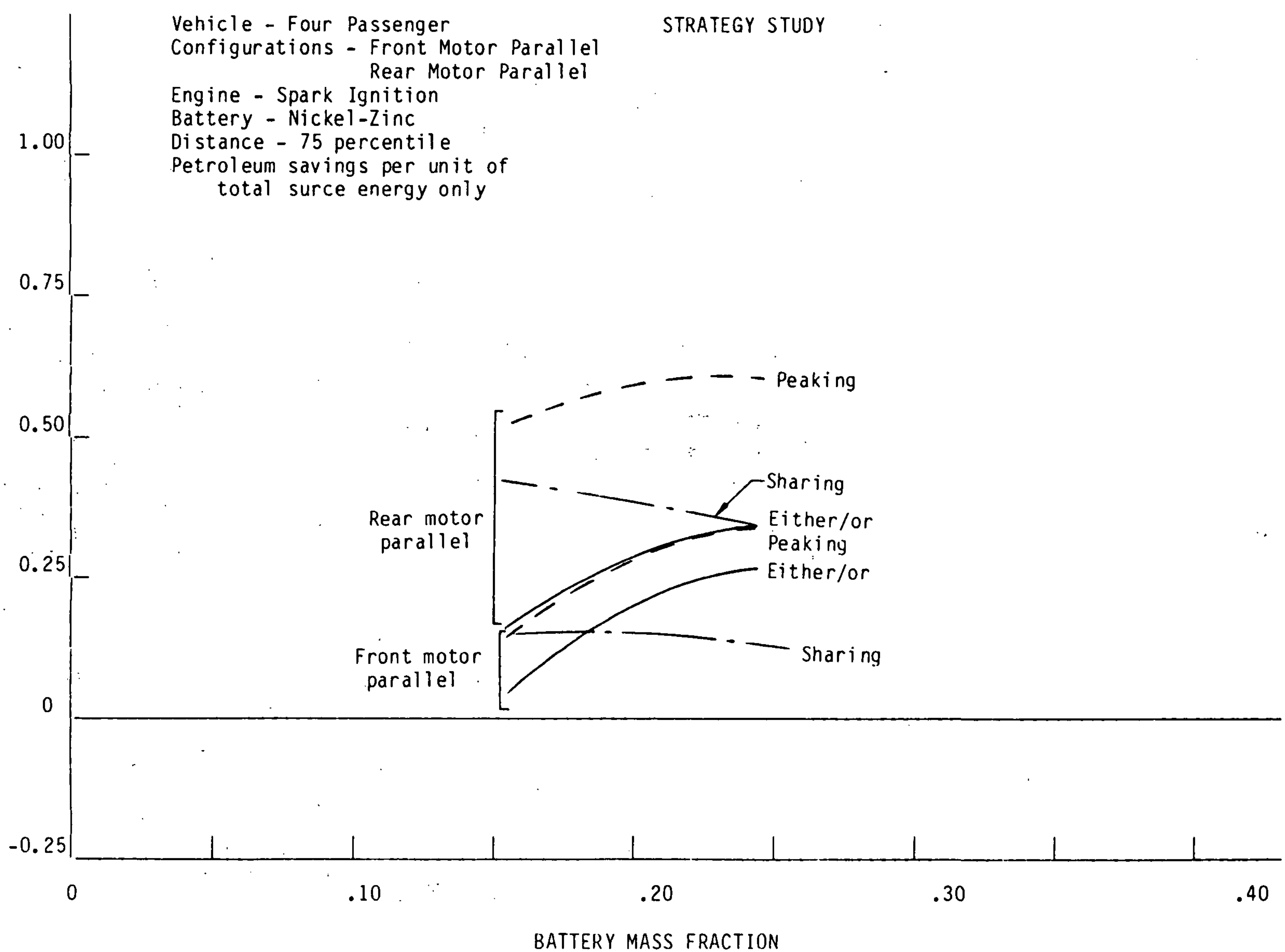


Figure C-28. Petroleum Savings for Four-Passenger Vehicle with Front-Motor and Rear-Motor Parallel Configurations

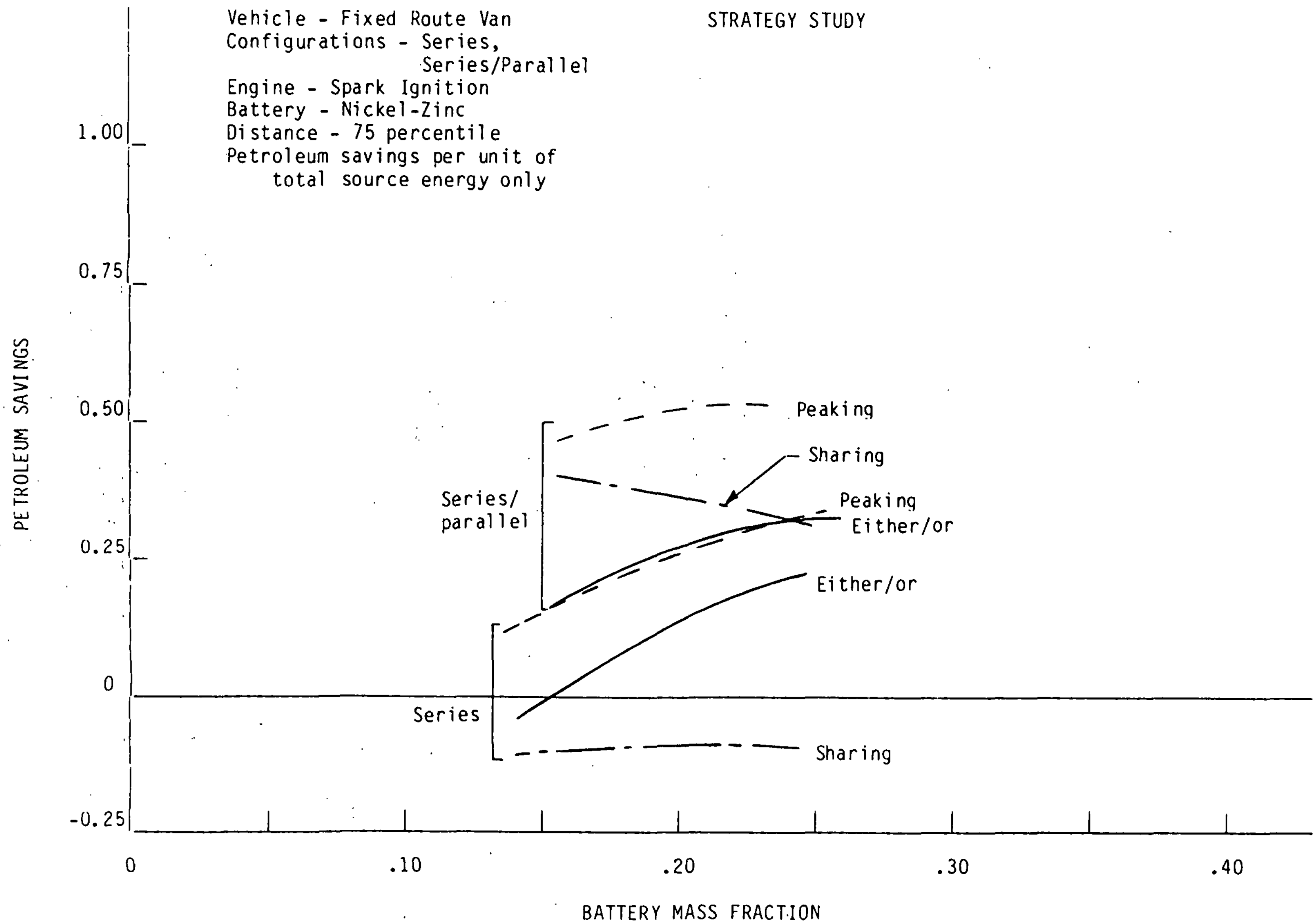


Figure C-29. Petroleum Savings for Fixed-Route Van with Series and Series/Parallel Configurations

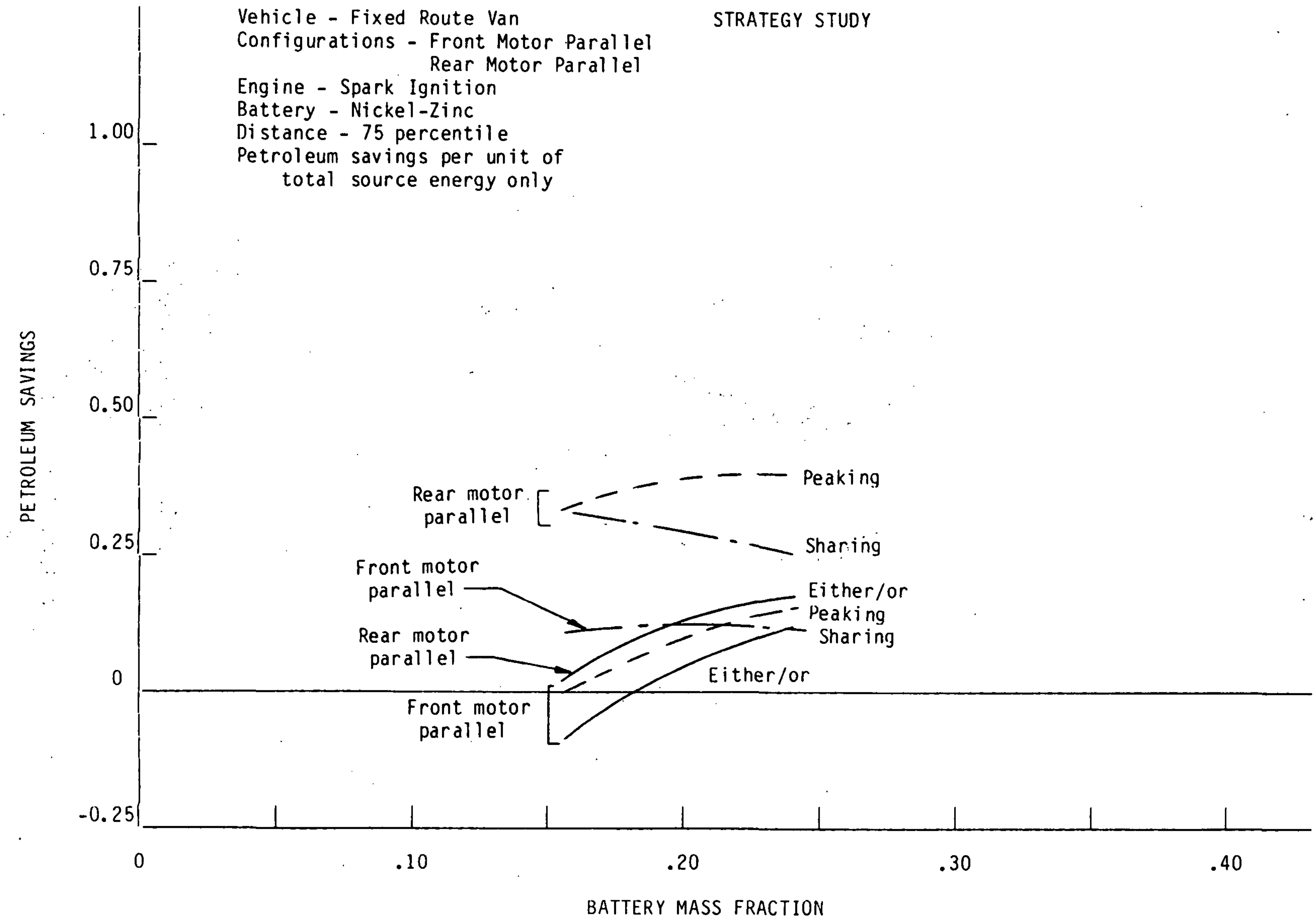


Figure C-30. Petroleum Savings for Fixed-Route Van with Front-Motor and Rear-Motor Parallel Configurations

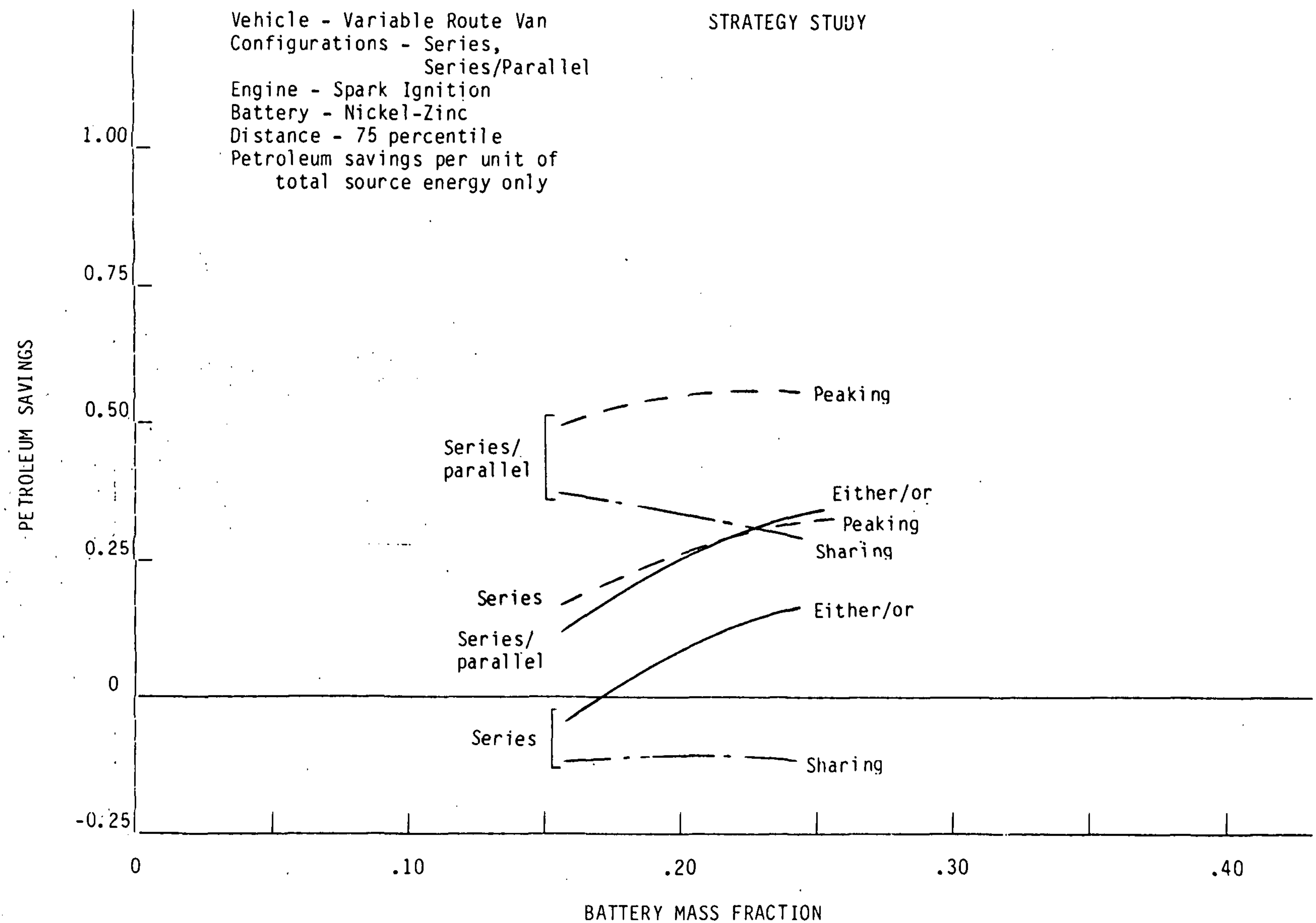


Figure C-31. Petroleum Savings for Variable-Route Van with Series and Series/Parallel Configurations

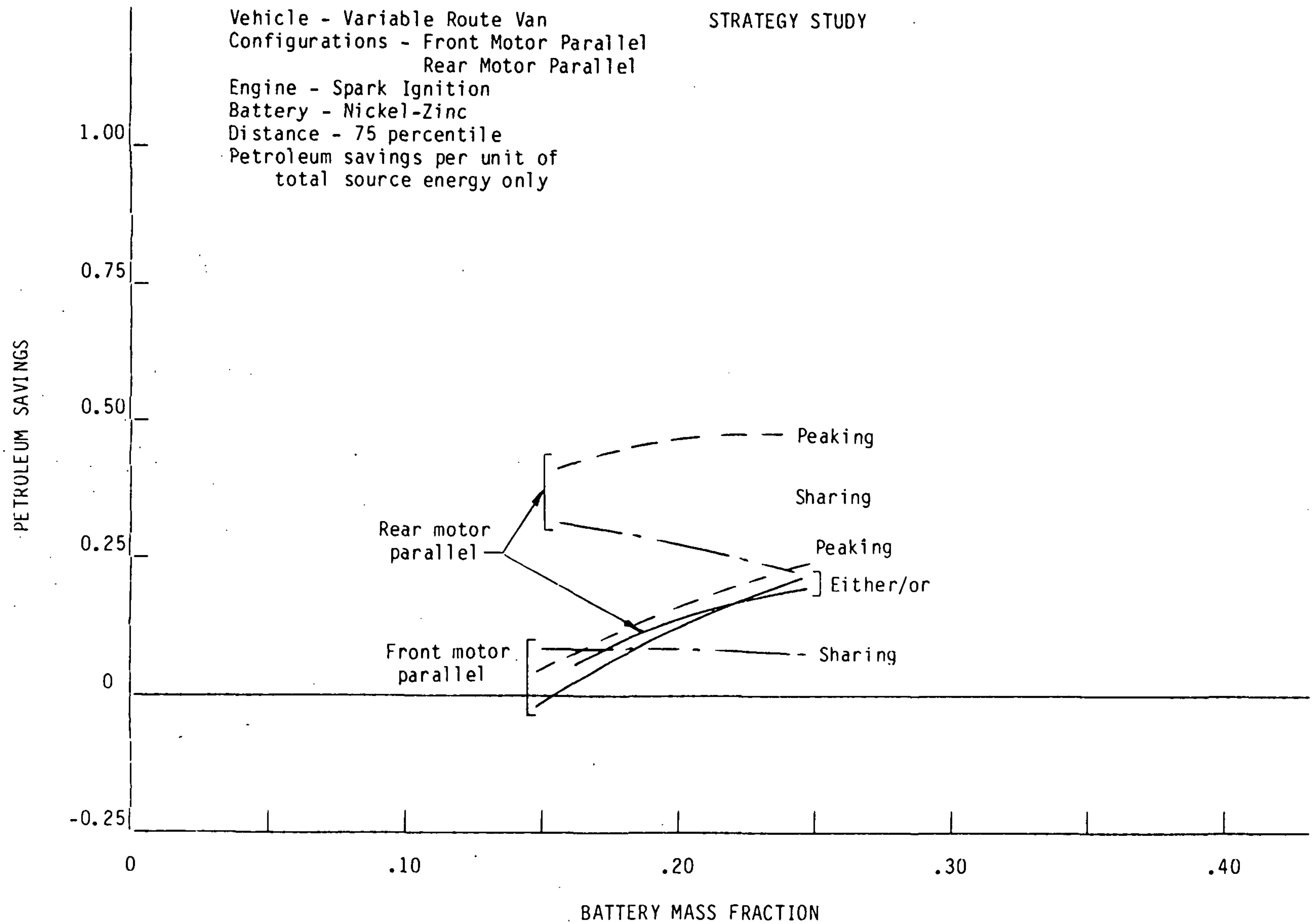


Figure C-32. Petroleum Savings for Variable-Route Van with Front-Motor and Rear-Motor Parallel Configurations

APPENDIX D

The four curves in this appendix show the relationship between the annual distance driven and the petroleum savings for the commuter, the four-passenger car, the five-passenger car, the fixed-route van, and the variable-route van. Results for these four vehicles differ markedly from each other. In addition, there are significant differences between the three petroleum savings curves.

In Figure D-1, the petroleum savings for the commuter car is shown. Both the petroleum savings per unit of reference vehicle fuel used show maxima in the 65th to 70th percentile range. Increasing the distance beyond 75 percentile sharply reduced savings.

In contrast, the four passenger car, shown in Figure D-2, does not show a maximum. The PS/RVF value decreases with an increasing distance traveled. The five passenger car, shown in Figure D-3, is virtually identical to the four passenger car.

The annual distance traveled has no effect on the PS/RVF for the fixed-route van shown in Figure D-4. For the variable-route van (Figure D-5), the curve decreases with increasing distance, but less steeply than the fixed-route van.

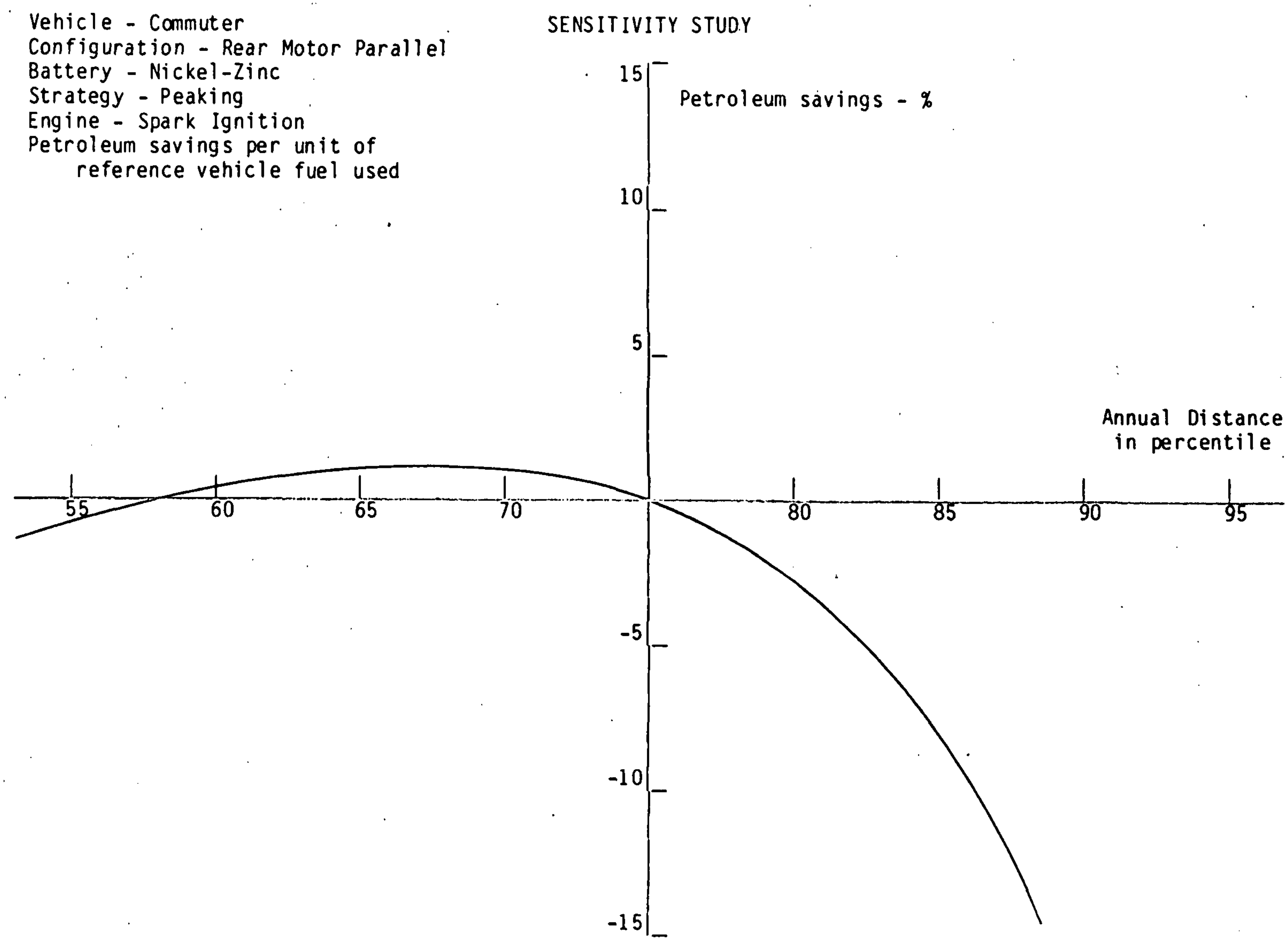


Figure D-1. Petroleum Savings as a Function of the Annual Distance Traveled

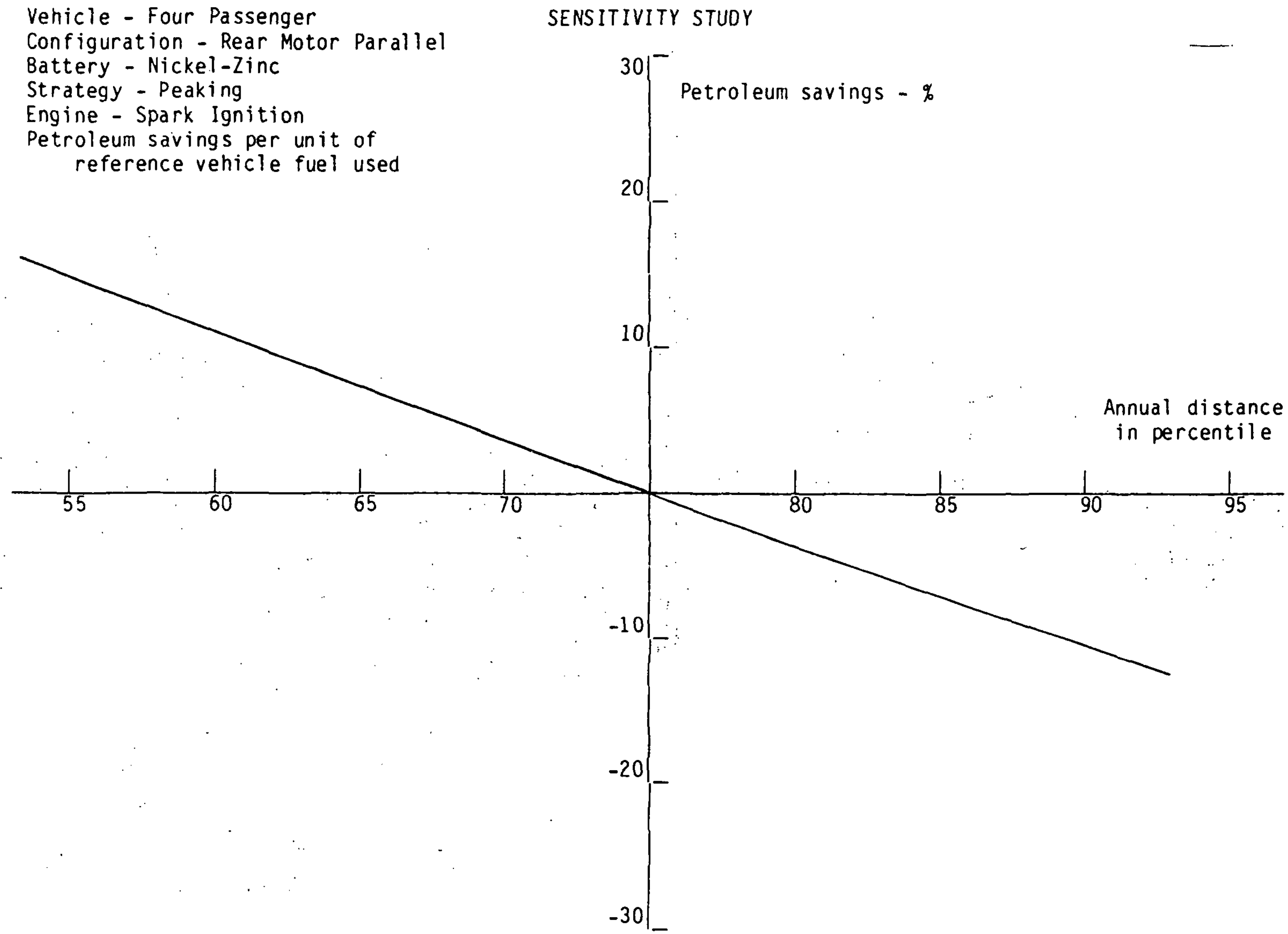


Figure D-2. Petroleum Savings as a Function of the Annual Distance Traveled

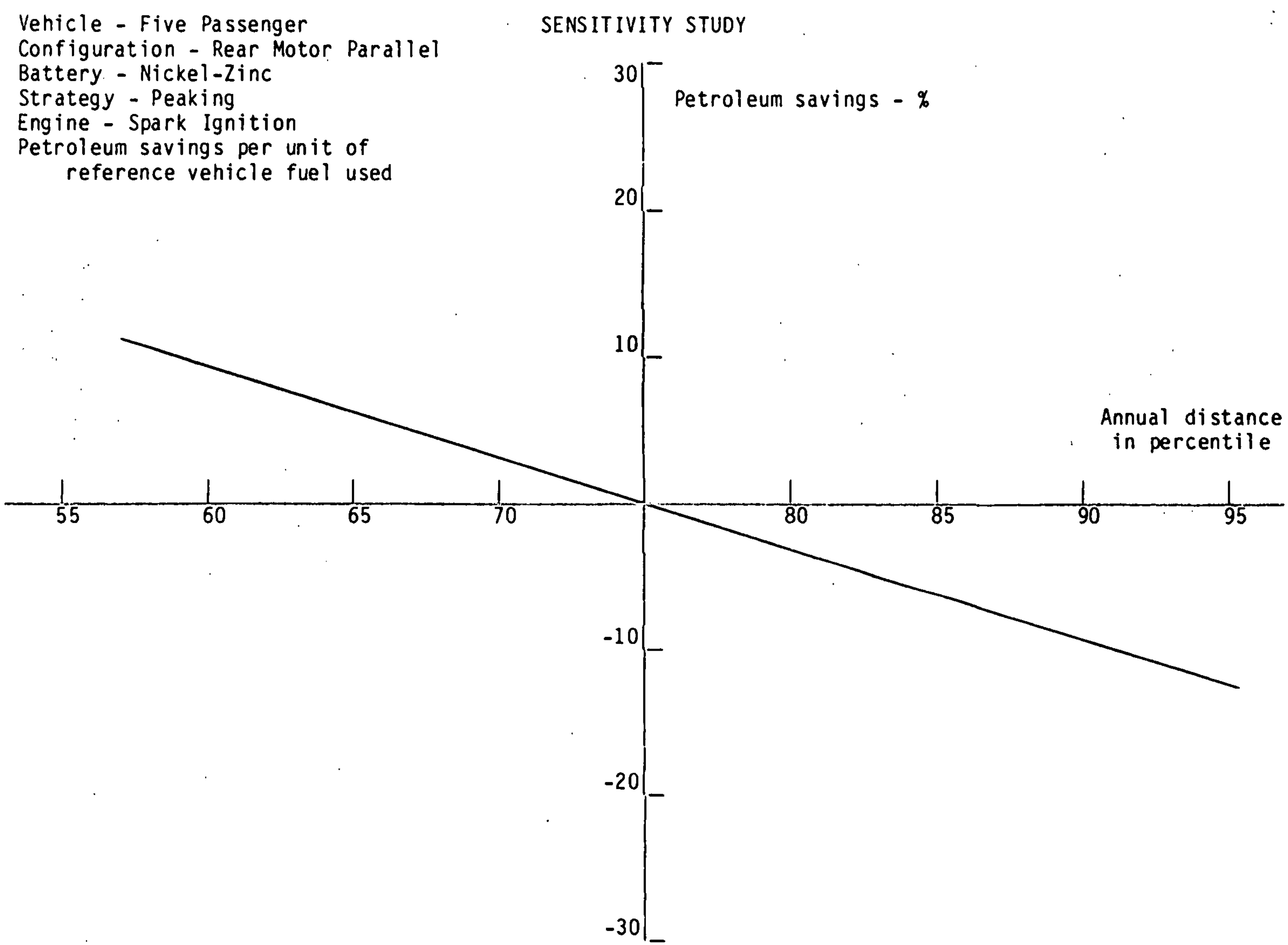


Figure D-3. Petroleum Savings as a Function of the Annual Distance Traveled

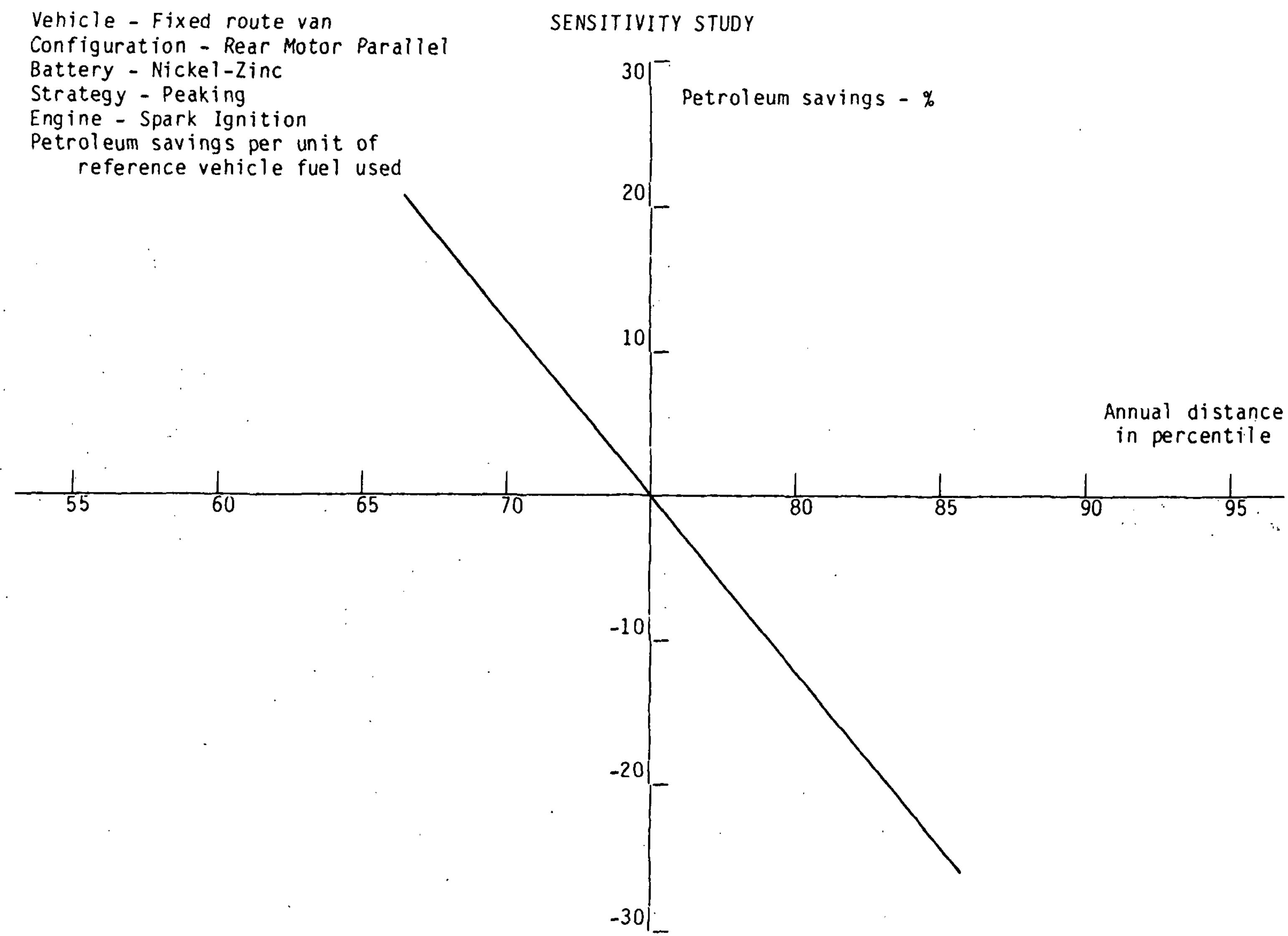


Figure D-4. Petroleum Savings as a Function of the Annual Distance Traveled

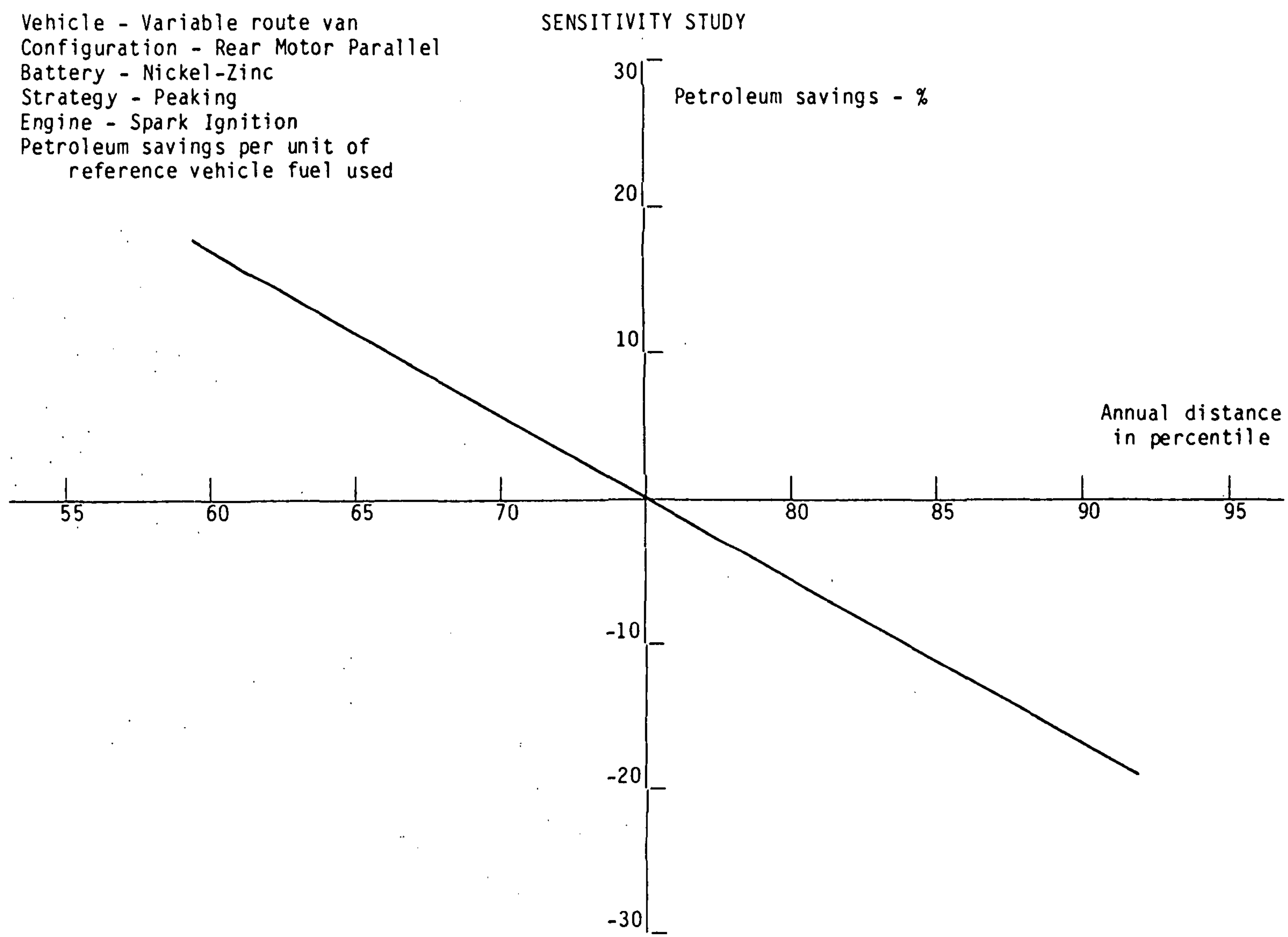


Figure D-5. Petroleum Savings as a Function of the Annual Distance Traveled

APPENDIX E

The HYVEC IV program structure is shown in Figure E-1. The top level of the program is MAIN2 which, with a Fortran procedure called HYPROC, controls program initialization and acts as the beginning and end of the entire program. MAIN2 calls the individual configuration-strategy combinations and the operating mode (steady speed, maximum acceleration, and driving cycle).

The next level, referred to as control programs, consists of 51 subroutines, one for each combination of configuration, strategy, and operating mode. The control programs call the component subroutines, the mathematical subroutines, and the data blocks. The data blocks contain the numerical data for specific vehicles and identify such items as chassis weight, frontal area, and rolling resistance coefficients.

Each major component of the various configurations is the subject of a separate subroutine which contains the mathematical model and the data for one or more variations. For example, there are 11 different engines in the heat-engine subroutine. The battery subroutine has three different mathematical models and data for over 40 batteries.[1] Some of this data are presented in Section V of the report in the discussion on components characteristics.

The output of the calculations is made in a subroutine referred to as OUTPUT. A typical run results in three pages of output in the form of an input page which lists the input parameters used for the particular run, a running page which shows the second-by-second simulation results, and a summary page which lists the losses associated with each compoment and the overall fuel and electricity use. By changing input parameters, one or all of the pages may be deleted, their formats changed, and different sets of parameters displayed. A set of typical pages are shown in Table D-1.

---

[1]Battery characteristics used in this analysis are the same as those used in the Advanced Vehicle Assessment at JPL.

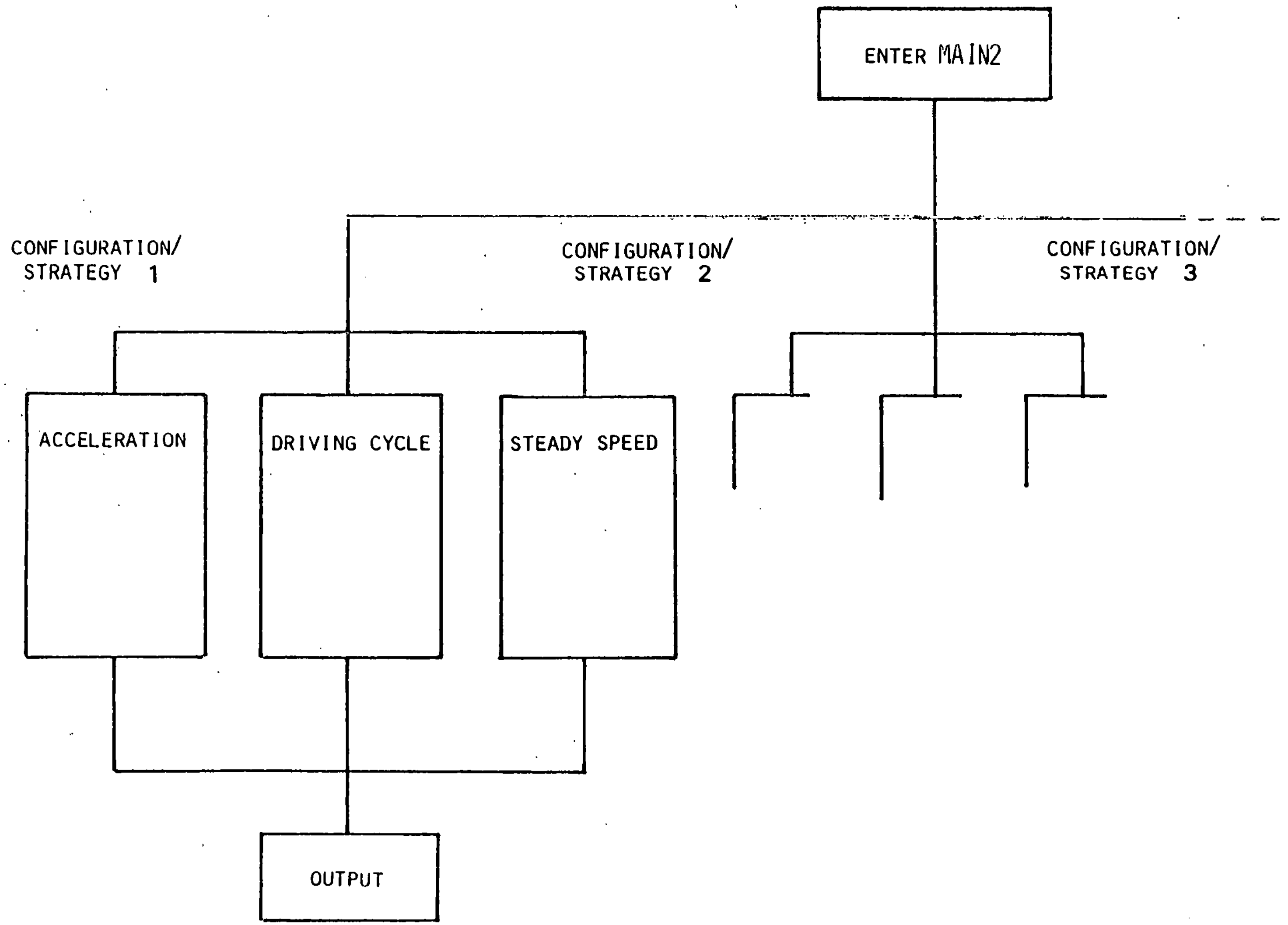


Figure E-1. HYVEC III Structure

Table D-1. Run 14

HYVEC RUN INFORMATION

DATE OF RUN	070283	TIME OF RUN	123641	MISSION NO.	21
CONFIGURATION	SERIES	ENERGY MGMT	PEAKING		
REGENERATIVE BRAKING?	YES	ENGINE ALWAYS ON?	NO		
VEHICLE TYPE	FIVE PASSENGER	VEHICLE MODE	DRIVING CYCLE		

VEHICLE INFORMATION

TOTAL VEHICLE MASS	1747. KG	CHASSIS MASS	763. KG
FRONTAL AREA	2.0 M**2	ROLLING RESISTANCE	.010
COEFFICIENT OF DRAG	.40	WHEEL DIAMETER	.64 M
INITIAL BATTERY CHARGE	1.00	MIN. BATTERY CHARGE	.200
HEADWIND VELOCITY	.0 M/S	GRADE	.00
BATTERY MASS FRACTION	.200	CURB MASS	1611. KG

COMPONENT INFORMATION

COMPONENT	TYPE NO.	PEAK POWER KW	MAX. SPEED RPM	MASS KG	SPECIFIC POWER KW/KG	POWER FRACTION	MOMENT OF INERTIA KG-M**2
ENGINE	11	42.4	5500.	122.	.347	.0263	.05241
MOTOR	1	34.5	4100.	92.	.375	.0214	.08298
TRANSMISSION	1	42.4	5500.	0.	*****		.00127
MOTOR TRANS.		34.5	4100.	0.	*****		.00000
GENERATOR		26.5	5500.	71.	.375	.0164	.07000
GEN. TRANS.		26.5	5500.	0.	*****		.00000
FLYWHEEL			0.	0.		.0000	.00000
FLYWHL. TRN.			0.	0.	1.500		.00127
MTR. CONTLR.		34.5		46.	.750		
BATT. CNTLR.		34.5		0.	.750		
BATTERY	30	61.2		322.	.190		
ACCESSORIES	1						

RATIOS AND EFFICIENCIES

DIFFERENTIAL	4.57	.960
MOTOR TRANS.	1.00	1.000
GEN. TRANS.	1.00	1.000

ACCESSORIES	USED?	ACCESSORIES	USED?
ENGINE FAN	YES	WATER PUMP	NO
AIR CONDITIONING	NO	ALTERNATOR	YES
POWER STEERING	NO	RADIO	YES
HEADLIGHTS	NO	HEATER BLOWER	YES

OTHER

ENGINE IDLE SPEED	900. RPM	IDLE FUEL FLOW	1.9 G/S
TORQUE CONVERTER DIA.	.33 M	T. CONV. INERTIA	.00065 KG-M**2
FLYWHL. MAX. ENERGY	.00 KW-H	FLYWHL. SP. ENERGY	.050 KW/KG
BATTERY SP. ENERGY	.110 KW/KG	INTEGRATION STEP SIZES	2.0, 120.

Table D-1. (Continued)

TIME SEC.	SPEED KM/H	ACCEL M/S**2	DIST KM	ENG. POWER KW	ENG. SPEED RPM	ENG. FUEL G/S	MOTOR POWER KW	BATT. STATE KW-S
.0	.0	.00	.00	.0	0.	.00	.0	127579.
90.0	49.4	-.04	.67	.0	0.	.00	2.7	126932.
2304.0	.0	.00	1.08	.0	0.	.00	.0	126778.
7704.0	.0	.00	1.08	.0	0.	.00	.0	126778.
13104.0	.0	.00	1.08	.0	0.	.00	.0	126778.
18504.0	.0	.00	1.08	.0	0.	.00	.0	126778.
21308.0	29.9	.42	1.32	.0	0.	.00	9.0	126422.
21398.0	89.2	.16	3.32	.0	0.	.00	20.5	123751.
21488.0	55.8	.22	4.50	.0	0.	.00	11.9	123121.
21578.0	56.5	.18	5.20	.0	0.	.00	10.7	122102.
21668.0	.0	-.74	6.12	.0	0.	.00	.0	121714.
22466.0	.0	.00	6.52	.0	0.	.00	.0	121445.
24503.0	15.4	-1.48	6.92	.0	0.	.00	-11.2	121149.
24593.0	34.6	.54	7.29	.0	0.	.00	12.7	120778.
24683.0	44.3	.02	8.05	.0	0.	.00	3.8	120139.
24773.0	43.8	-.22	9.18	.0	0.	.00	-2.2	119600.
24863.0	44.6	-.22	10.08	.0	0.	.00	-2.2	119096.
24953.0	43.5	-.16	10.71	.0	0.	.00	-.6	118730.
25043.0	.0	.00	11.29	.0	0.	.00	.0	118487.
28850.0	.0	.00	11.40	.0	0.	.00	.0	118292.
34250.0	.0	.00	11.40	.0	0.	.00	.0	118292.
35579.0	39.6	-.02	11.82	.0	0.	.00	2.2	117863.
35669.0	.0	.00	12.48	.0	0.	.00	.0	117618.
35759.0	89.8	-.22	14.03	.0	0.	.00	1.6	115110.
35849.0	.0	.00	15.64	.0	0.	.00	.0	114631.
35939.0	.0	.00	16.46	.0	0.	.00	.0	113810.
36029.0	32.3	.45	17.24	.0	0.	.00	10.2	113003.
36119.0	31.4	-1.48	17.90	.0	0.	.00	-22.4	112659.
36209.0	29.3	.60	18.25	.0	0.	.00	11.7	112418.
38010.0	.0	.00	18.71	.0	0.	.00	.0	112133.
43410.0	.0	.00	18.71	.0	0.	.00	.0	112133.
48810.0	.0	.00	18.71	.0	0.	.00	.0	112133.
54210.0	.0	.00	18.71	.0	0.	.00	.0	112133.
59610.0	.0	.00	18.71	.0	0.	.00	.0	116618.
65010.0	.0	.00	18.71	.0	0.	.00	.0	122074.
70410.0	.0	.00	18.71	.0	0.	.00	.0	123916.
75810.0	.0	.00	18.71	.0	0.	.00	.0	124837.
81210.0	.0	.00	18.71	.0	0.	.00	.0	125248.
86610.0	.0	.00	18.71	.0	0.	.00	.0	125248.
86850.0	.0	.00	18.71	.0	0.	.00	.0	125248.

Table D-1. (Continued)

MISSION NO.	DIST TRAVEL KM	TOTAL FUEL KG	FUEL ECONOMY KM/L	ENG-O ENERGY KW-H	TRANS LOSS KW-H	MOTOR LOSS KW-H	BRAKE ENERGY KW-H	DIFF. LOSS KW-H
22	11.00	.00	-.00	.00	.00	.43	.00	.09

ROLL RESIS KW-H	AERO ENERGY KW-H	ACCEL ENERGY KW-H	GRADE ENERGY KW-H	HDWND ENERGY KW-H	WHEEL INERT KW-H	WHEEL ENERGY KW-H	DRIVE ENERGY KW-H	REGEN ENERGY KW-H
.57	.33	.00	.00	.00	.00	.90	1.52	-.62

BATT COND KW-H	BAT-O ENERGY KW-H	BAT-I ENERGY KW-H	BATT LOSS KW-H	NET B ENERGY KW-H	MG TRN LOSS KW-H	CVT LOSS KW-H	FW COND KW-H	FW LOSS KW-H
34.86	2.68	2.10	6.12	3.11	.00	.00	.00	.00

GENTRN IN ENER KW-H	GENTRN LOSS KW-H	GEN IN ENER KW-H	GEN LOSS KW-H	GEN OUTPUT KW-H	CNTLP LOSS KW-H	ENG ACC KW-H	BAT ACC KW-H	MTR ACC KW-H
.00	.00	.00	.00	.00	.08	.00	4.22	.00

T.C. LOSS KW-H	T.C. LOSS KW-H	SPIN LOSS KW-H	PUMP LOSS KW-H
.00	.00	.00	.00

APPENDIX F

This appendix deals with the characteristics of the components used in the vehicles designed for each of the five missions studied. Table F-1 shows the basic HV design and performance parameter values used in the study. The five missions involve the commuter car, the four-passenger two-door car, the five-passenger sedan, the fixed-route delivery van, and the variable-route van.

The component characteristics used in the analysis are shown in the following figures of this appendix and Table F-2. Figure F-1 shows the normalized engine map for the spark-ignition engine. This map is based on the

Table F-1. Basic HV Design and Performance Parameters

Vehicle	Commuter	Four-Passenger	Five-Passenger	Fixed-Route Van	Variable-Route Van
Chassis mass, kg	400	565	763	942	1226
Frontal area, m^2	1.6	1.8	2.0	2.5	3.3
Coefficient of drag	0.40	0.40	0.40	0.48	0.48
Tire rolling resistance, N/N	0.010	0.010	0.010	0.010	0.010
Payload, kg	136	136	136	136	136
Number of passengers	2	4	5	-	-

Table F-2. Characteristics of Other Components

Gear Box	Ratios[a]	Efficiency
First gear	2.80 to 3.47	0.94
Second gear	1.70 to 1.85	0.96
Third gear	0.70	0.98
Differential	2.69 to 3.47	0.96
Motor and generator transmission	1.54	0.98 to 1.00

[a]Ratios depend on the specific vehicle. Motor controller is rated to motor demand with 0.98% efficiency; wheels are sized to fit the curb weight.

Buick V-6 engine used in many General Motors intermediate-sized cars. It is typical of modern production engines. Figure F-2 shows the normalized engine map for the diesel engine used in this study. Based on the Mercedes-Benz three-liter engine, it represents one of the most popular European diesel engines.

Figures F-3 and F-4 show the motor map and generator map, respectively. This dc motor is state of the art and a significant improvement in efficiency is not expected. Gains in motor design might reduce weight and possibly volume, but not efficiency. There is little difference in efficiency between the dc motor and the ac motor with an inverter. These differences are primarily in size, weight, and packaging, and these items have little effect on petroleum savings.

The generator characteristics are shown also. As in the case of the motor, a 60% overload is permitted for a short time.

The power-energy characterics for ten batteries are shown in Figures F-5 to F-8. These curves were constructed from the ELVEC battery model, employing the battery characteristic coefficients developed by JPL during the Advanced Vehicle Analysis of 1981 to 1983. These results were transferrred to the HVA with only one modification, the use of an estimated optimum depth[1] of discharge for each battery type. These were JPL estimates and are admittedly uncertain. A recommendation is made for the collection of better depth of discharge data in future battery development work. These estimates were as follows:

Battery	Optimum Depth of Discharge
Ni-Zn	0.9
Ni-Fe	0.7
Pb-A	0.5
Zn-Br	1.0
Zn-Cl	1.0
$Li-Fe-S_2$	0.8
Li-Fe-S	0.8
Na-S	0.9
Fe-Air	0.9
Al-Air	1.0

The appearance of a battery on this list does not imply its readiness for HV by 1990. It is only to indicate that the estimated power-energy characteristics and the estimated optimum depth of discharge were used to assess its suitability for petroleum savings.

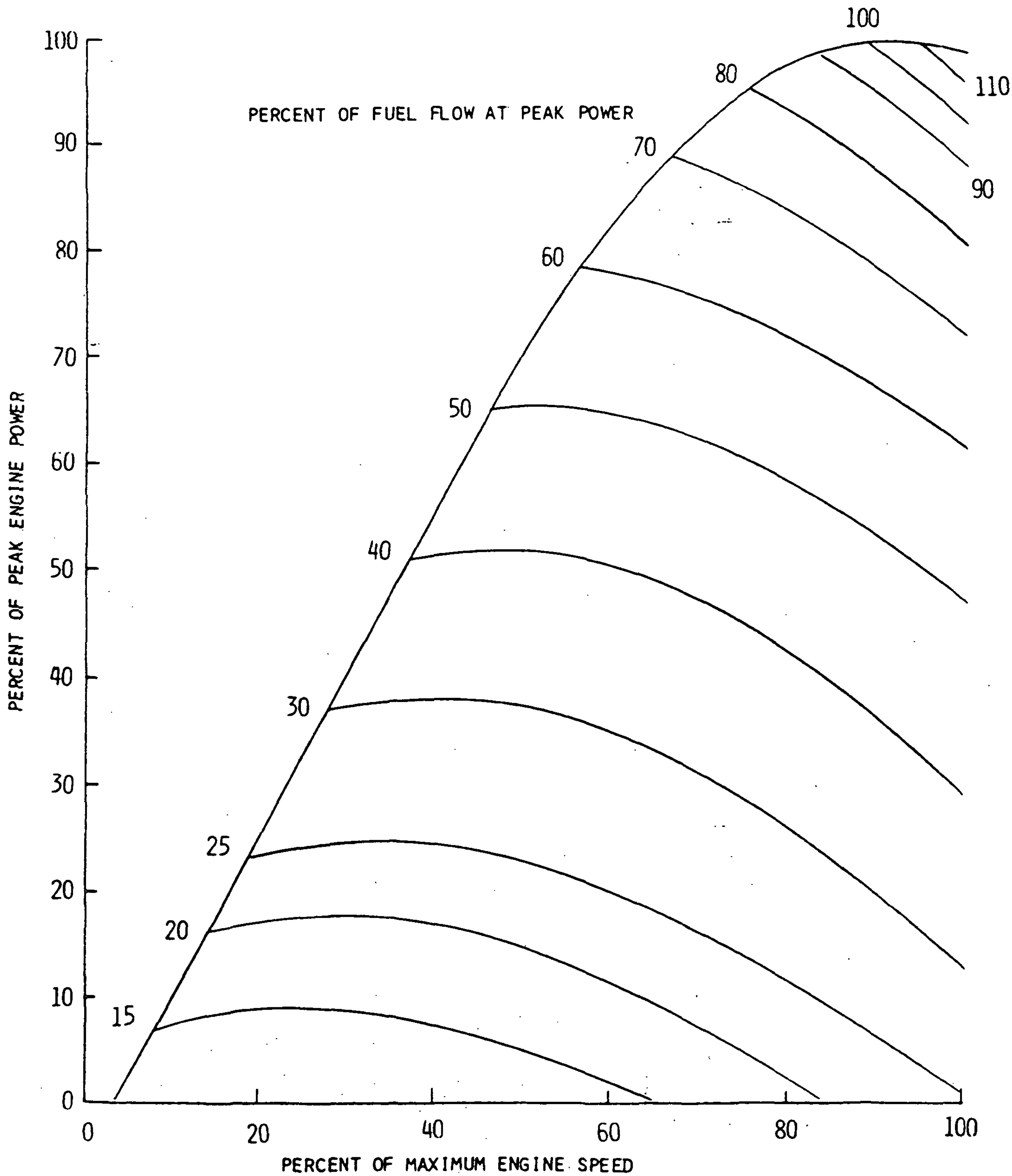


Figure F-1. Spark-Ignition Engine Map

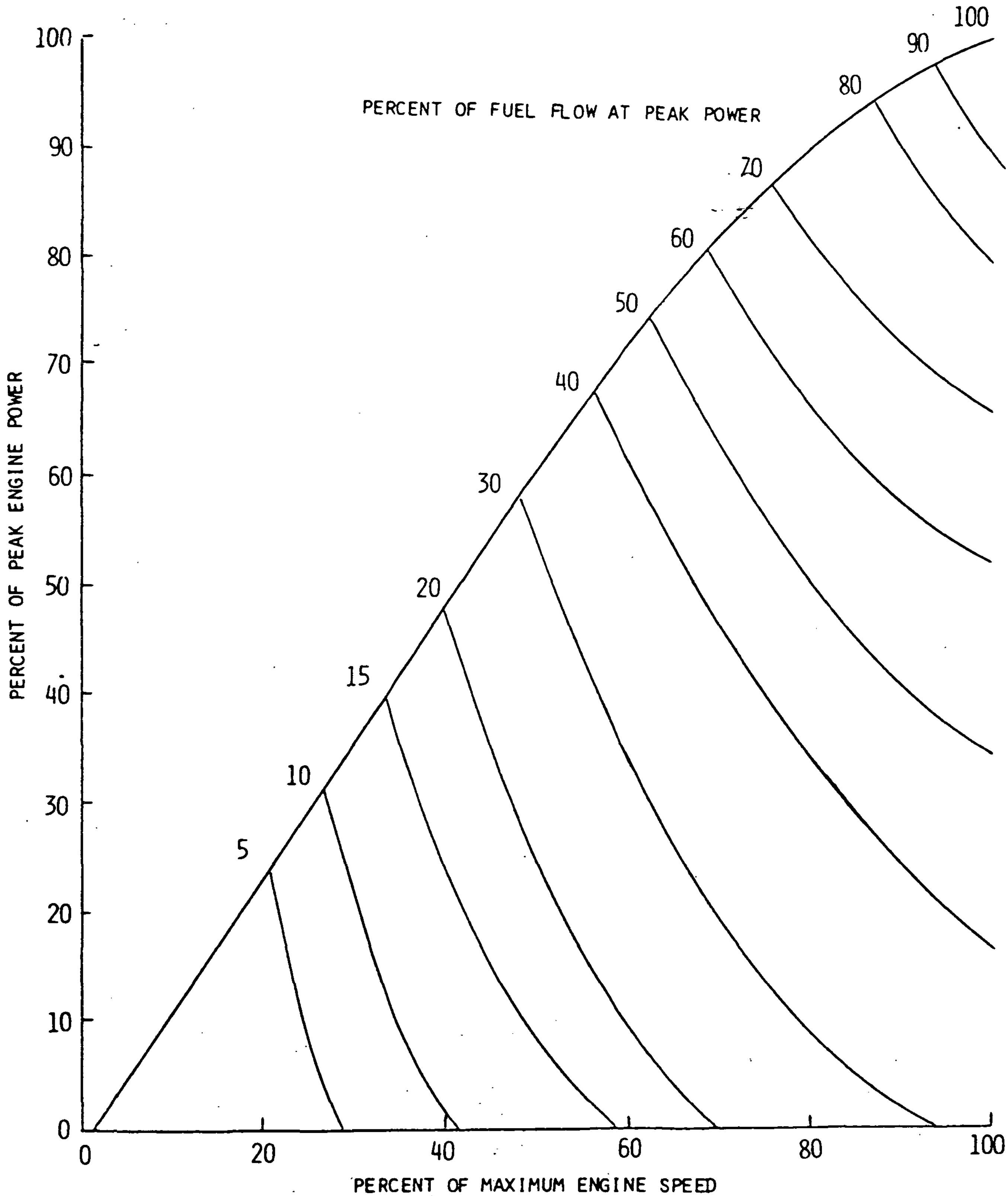


Figure F-2. Diesel Engine Map

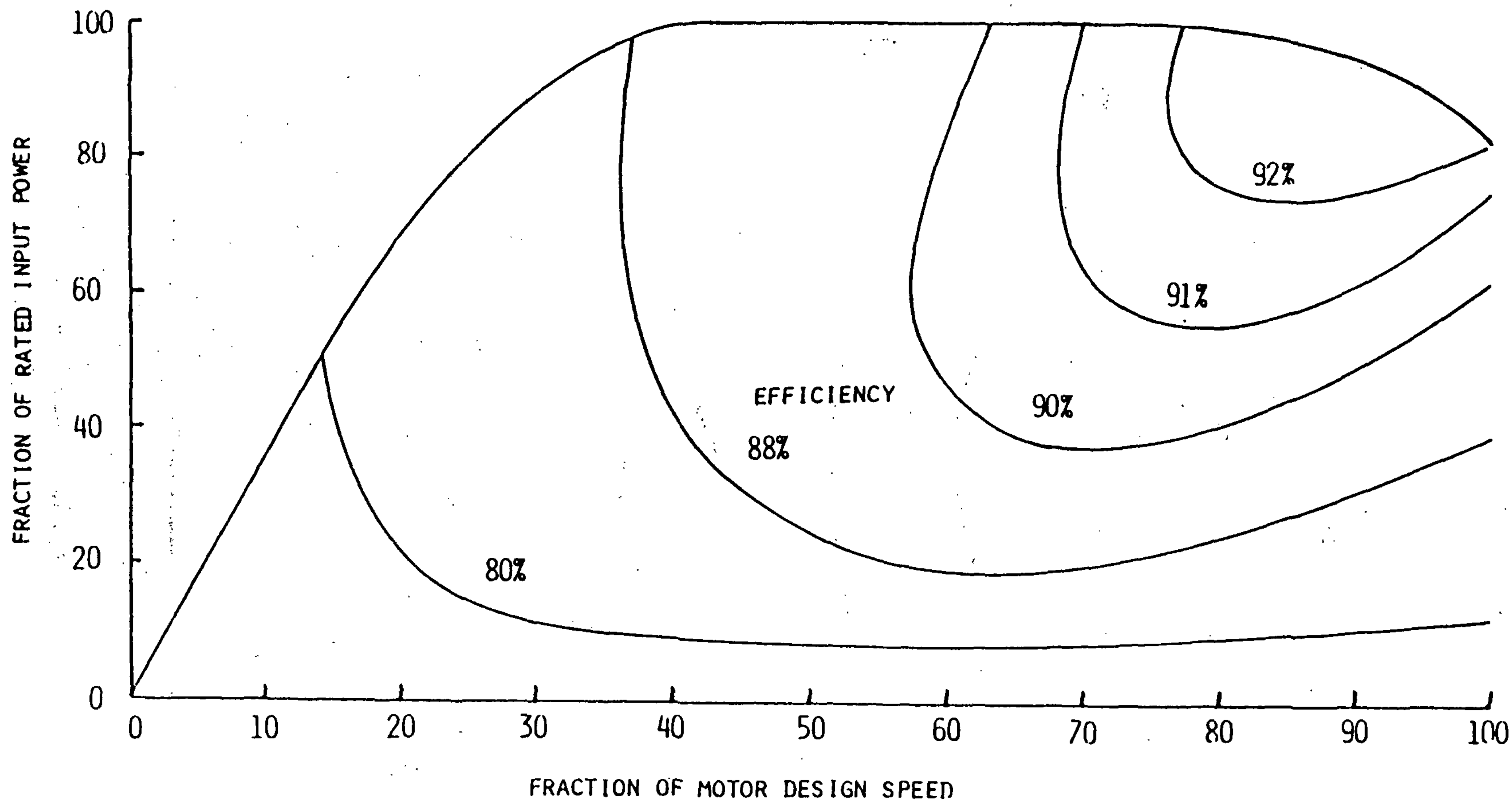


Figure F-3. Direct-Current Motor Map

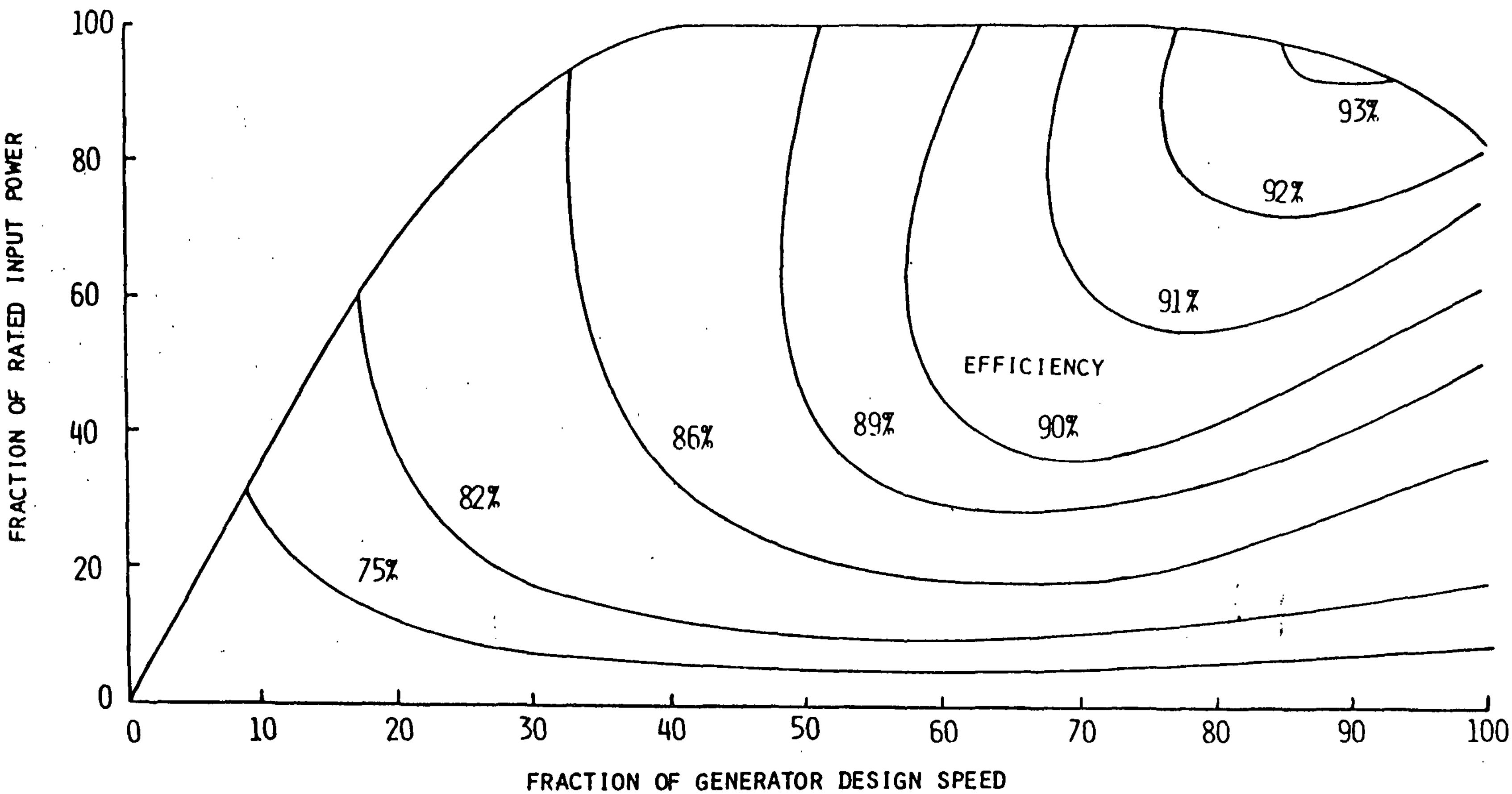


Figure F-4. Direct-Current Generator Map

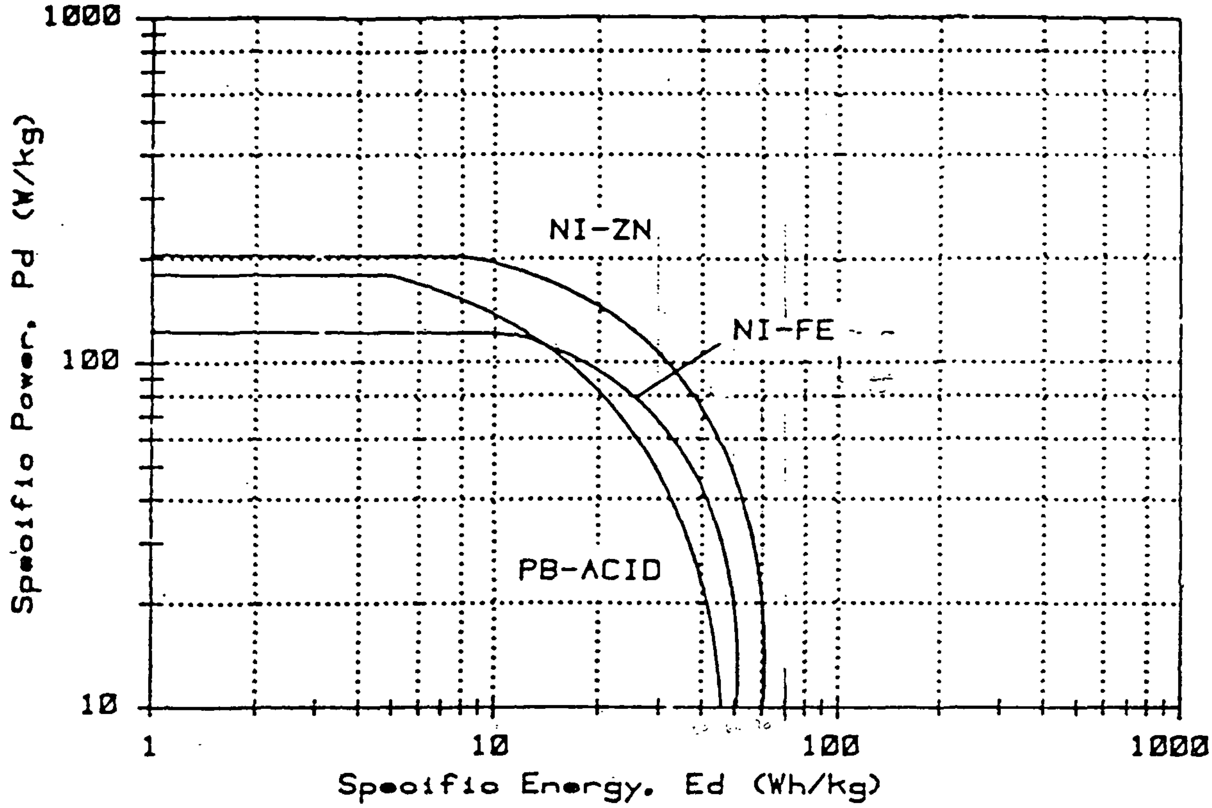


Figure F-5. Aqueous Mobile Battery Discharge Curves

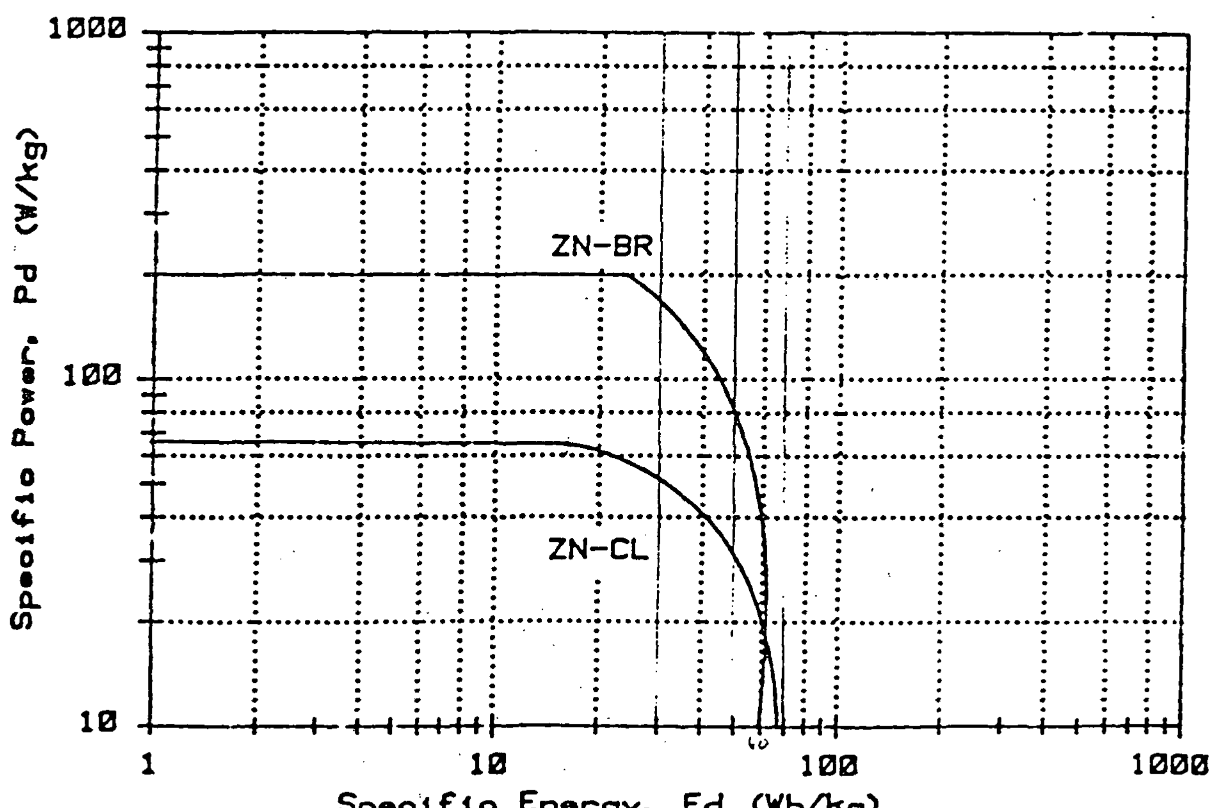


Figure F-6. Flow Battery Discharge Curves

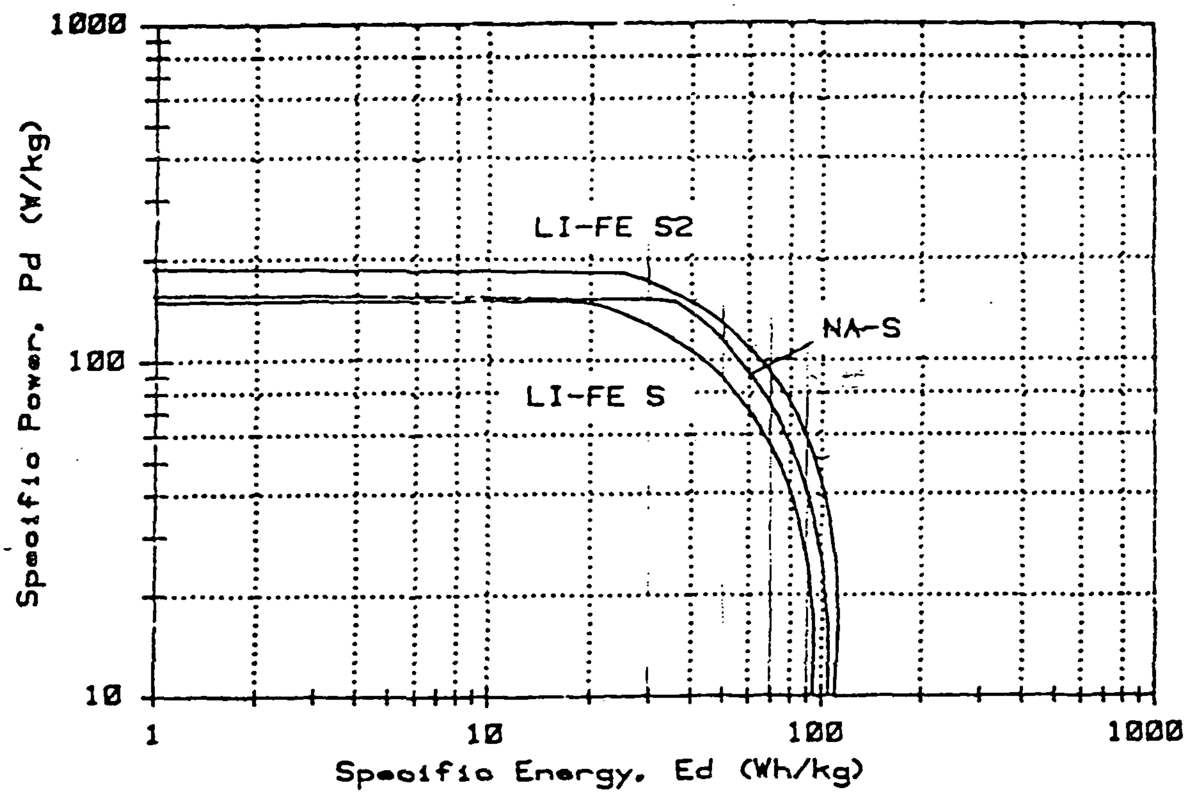


Figure F-7. High-Temperature Battery Discharge Curves

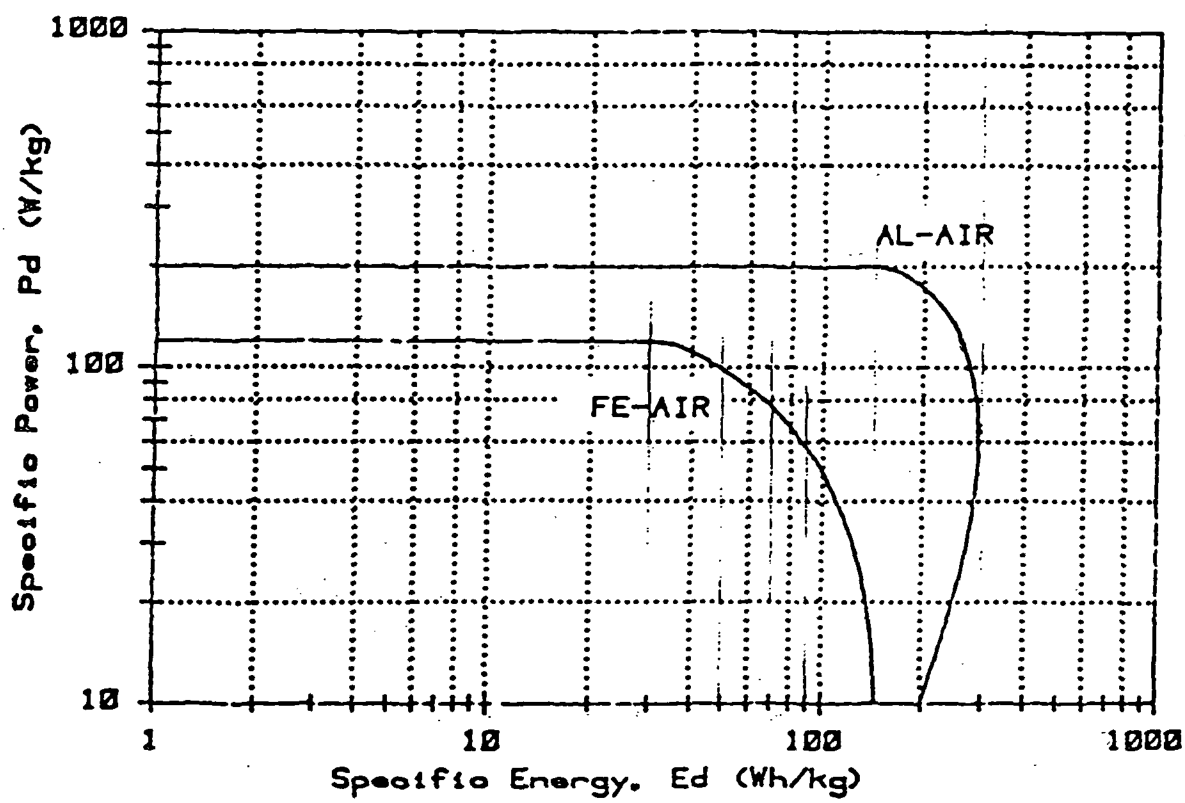


Figure F-8. Metal-Air Battery Discharge Curves

These power-energy plots can be interpeted as battery power-efficiency curves. The maximum energy available from the battery is limited and occurs at a discharge rate of about 1 W/kg, far less than practical specific power levels. At higher power levels, where less useful energy is obtained from the battery, the discharge efficiency is defined as the ratio of the useful energy to the maximum energy.

The maximum power from the batteries represented by these curves has been limited to values somewhat lower than that which the battery could achieve. This limit is controlled by the conflicting demands for high power, a specified size for the motor controller, and discharge efficiency. A high power level results in a large, expensive controller and low battery efficiency. The power level chosen is usually between 100 and 200 W/kg. The discharge efficiency at maximum power is typically 20 to 30%, but may be as low as 10% or as high as 50%, depending on the battery.

The maximum power that a battery can supply is also limited by the battery state of charge. In Figure F-9, the normalized maximum power is shown as a function of the state of charge for the same 10 batteries. The primary batteries (aluminum-air, zinc-chlorine, and zinc-bromine) show little or no change in maximum power until they are totally discharged. The other extreme is represented by the lead-acid batteries which show a significant decrease in maximum power early in the discharge cycle. The remaining batteries lie between these extremes. With the exception of the primary batteries, once a battery is below a 10% state of charge, the maximum power decreases so rapidly that it is no longer useful for drive power. (The lead-acid battery reaches this condition at about a 20% state of charge.)

The clutches used in this study are primarily isolation clutches, are either open or closed, and involve losses. In the HTV, a modulated or slipping clutch is used which does have losses. Ideally, there is no torque loss across a slipping clutch, but speed differences are experienced. The efficiency of the clutch is equal to the speed ratio (the ratio of the output speed to the input speed).

The torque converter used in the front motor parallel configuration has both torque and speed losses, but it is more efficient than the slipping clutch when the speed ratio across the converter is low. The torque ratio-speed ratio curve for the torque converter used in this study is shown. At a speed ratio of 0 (output speed equal to 0), the torque ratio is 2.45 and drops as speed ratio increases until the converter reaches the coupling point after which it is 1.0. The coupling point is reached when the converter ceases to act as a converter and becomes an hydraulic coupling. (A hydraulic coupling is the fluid analog of a slipping clutch with a torque ratio of 1.0 and the efficiency equal to the speed ratio.) The efficiency of either a torque converter or a hydraulic coupling is the product of the torque ratio and the speed ratio. The efficiency of this converter is also shown on Figure F-10.

The power absorbed by a torque converter is

$$P = CFN^3$$

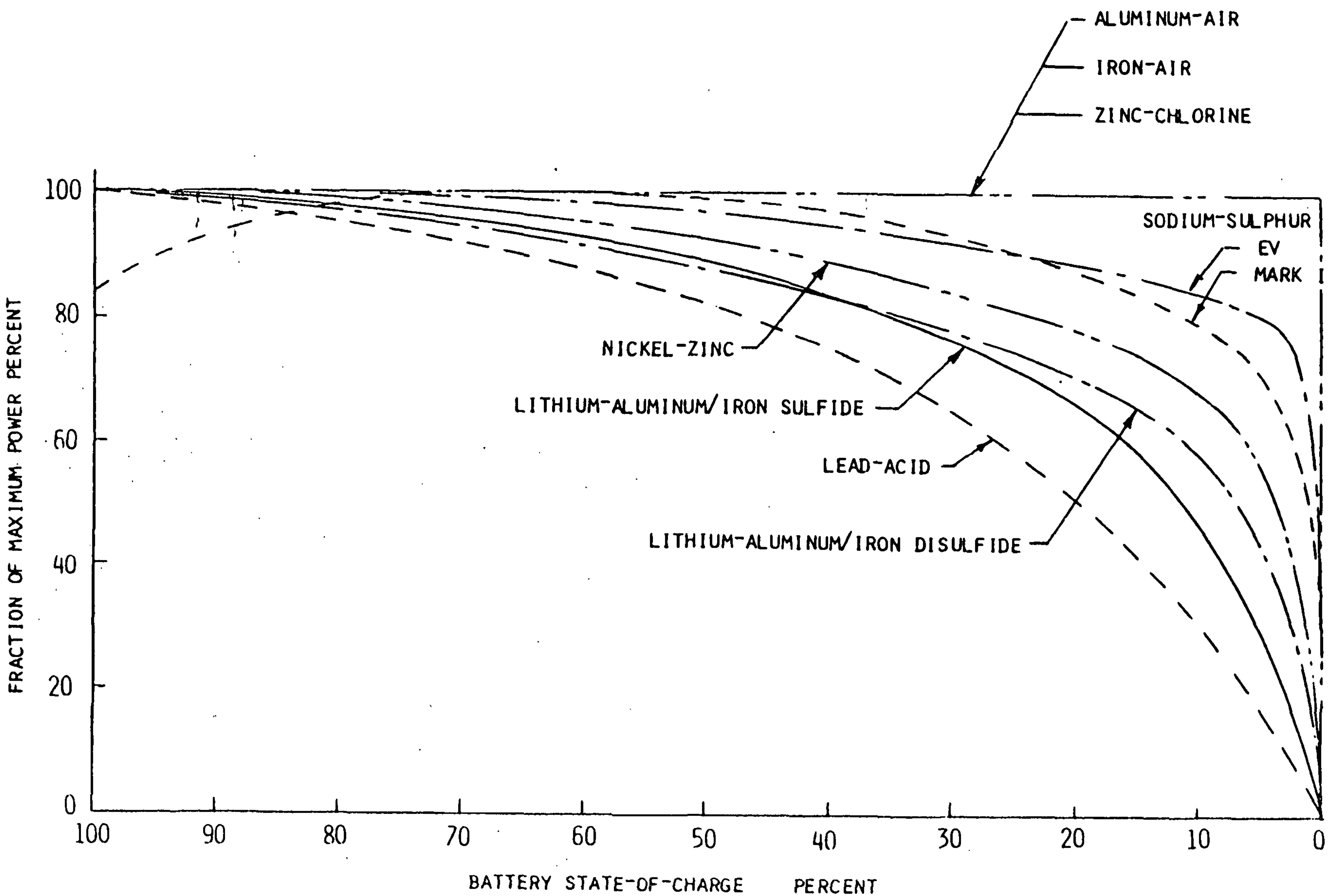


Figure F-9. Battery Maximum Power Curves

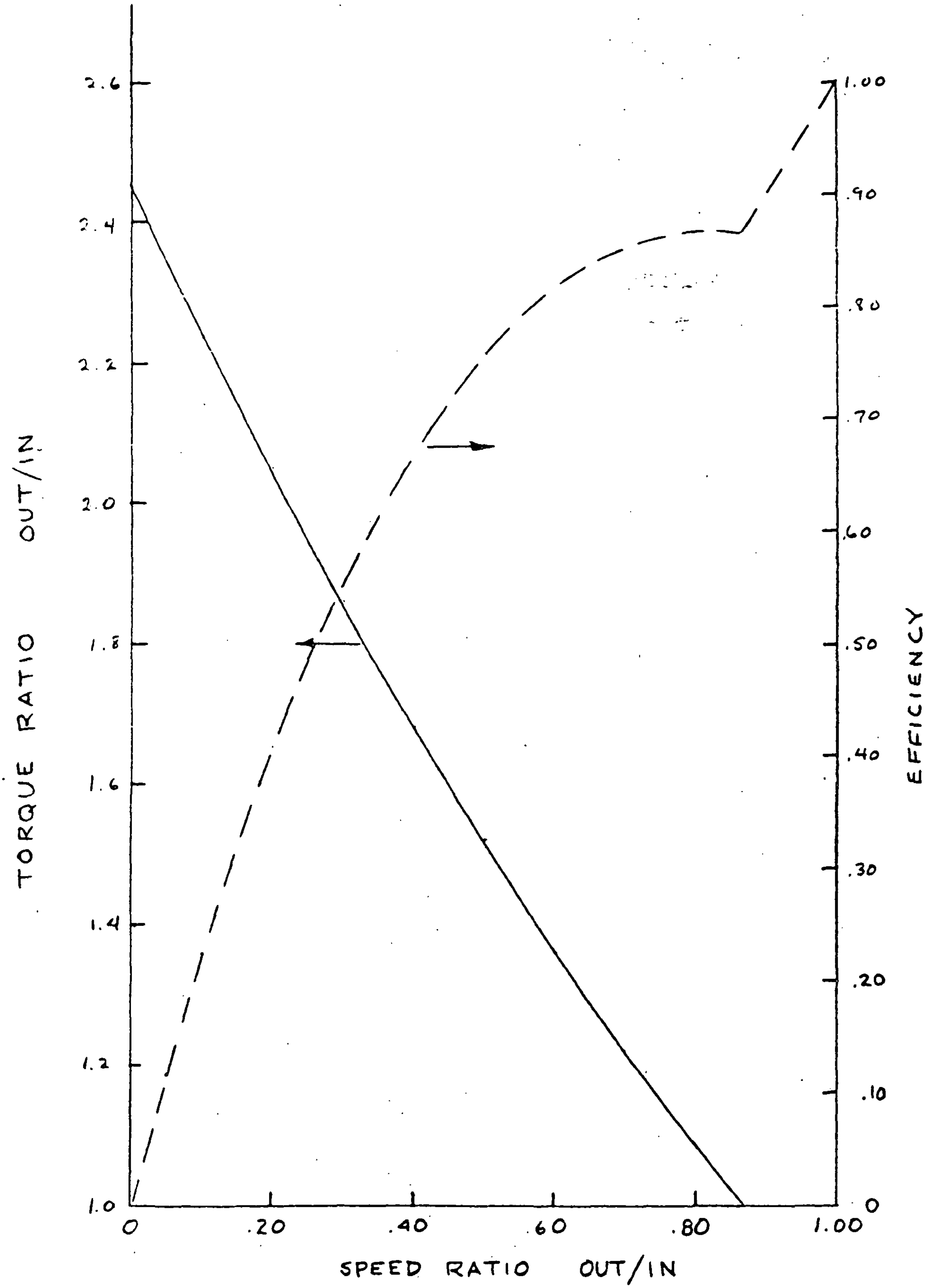


Figure F-10. Torque Converter Characteristics

where P is the input power, CF is the power capacity factor, and N is the input speed. CF can be further expressed as

$$CF = D^5 f(sr)$$

where D is the diameter, and f(sr) is a function of the speed ratio and the design of the converter blading. The capacity factor is usually determined from tests on actual hardware because the losses involved are difficult to determine analytically. By scaling the diameter, the torque converter input is matched to the engine output.

Vehicle accessories provide a significant power load. In Figure F-11, the design power vs speed curves for the accessories used in this study are shown. The accessories can be divided into three groups, the engine, the drive line, and the electrical accessories. The engine accessories are those used only when the engine is running, i.e., the radiator fan. Drivetrain accessories are those needed regardless of which energy source is being used, i.e., air conditioning, power steering, etc. Electrical accessories include the radio and headlights. The actual power used by the car is scaled up or down from the design levels, depending on the engine or motor sizes.

A number of other component characteristics are shown in Table F-2. All of these depend on the details of the specific vehicle and a range of typical values are shown here. They do not reflect actual values for a specific vehicle.

A manual transmission was used for many of the vehicles. It has first-gear ratios in the 3.0 to 3.5 range. The front motor parallel HV used a torque converter and the gear ratios are lower (in the 2.80 to 3.0 range). In general, the second gear ratio is approximately the square root of the first gear ratio. The third gear ratio is 1.0. Only three-speed gear boxes were used in this study.

The differential ratios also depend upon whether a torque coverter is used. Generally, the torque converter requires a lower ratio differential than the manual transmission. The lower gear ratio with the torque converter results from the torque multiplication characteristic of the converter. The overall torque multiplication ratio from engine to wheels (the product of all of the gear and the converter ratios) is similar for both transmission systems.

Only a few configurations involve either a motor or a generator transmission. Their use depends upon whether it is necessary to run the motor or generator at a different speed from the engine or wheels. In the few cases where they are used, the speed ratio corresponds to the maximum motor output speed, divided by the differential input speed for the maximum vehicle speed.

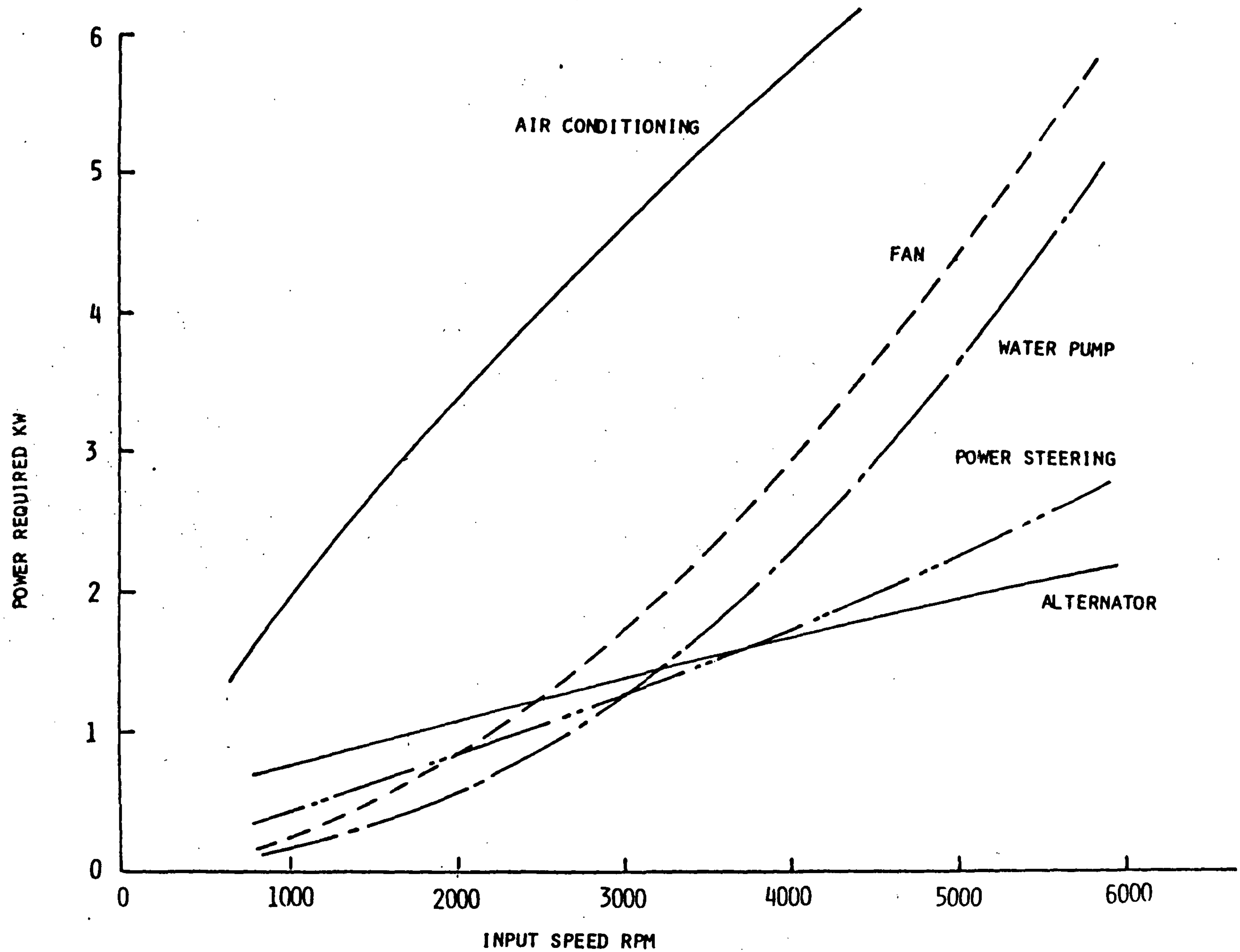


Figure F-11. Accessory Power Requirements